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R78-1
JANUARY 1978

CR151735

(NASA-CR-151735) ELECTROMECHANICAL FLIGHT
CONTROL ACTUATOR, VOLUME 3 Final Report
(Delco Electronics, Santa Barbara, Calif.)
188 p HC A09/MF A01 CSCL 13F

N78-25987

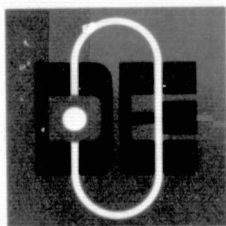
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FINAL REPORT ON THE
**ELECTROMECHANICAL
FLIGHT CONTROL ACTUATOR**

VOLUME 3

CONTRACT NAS 9-14952

Submitted to
NATIONAL AERONAUTICS and SPACE ADMINISTRATION
L.B. Johnson Space Center
Houston, Texas



Delco Electronics

General Motors Corporation
- Santa Barbara Operations
Santa Barbara, California

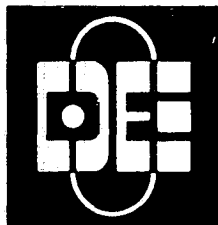
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- Santa Barbara Operations
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FOREWORD

This report is divided into three volumes. Volume 1 is the body of the report, Volume 2 contains Appendices A through I, and Volume 3 contains Appendices J through L.

APPENDIX J

DESIGN VERIFICATION TEST RESULTS

This appendix presents Delco document EE-22T-EMA-021 which covers the design verification tests which were conducted on the electromechanical actuator.



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EE- 22-T-EMA-021

ENGINEERING EXHIBIT
(NO CHANGE CONTROL)

TITLE: Electromechanical Actuator Design
Verification Tests

BY: J. Anselmi

APPROVED:

DATE:

INTRODUCTION

A number of tests have been conducted on the Electromechanical Actuator (EMA) to determine its performance characteristics. In most instances, the tests were performed to compare the actual performance of the EMA against the design goals of the NASA Statement of Work (SOW). Unless otherwise noted, all paragraphs referenced in the following pages are those of the NASA SOW.

The following paragraphs summarize the testing activities, discussing briefly the methods used to conduct the tests, the test data which were obtained, and a comparison of achieved performance against design goals.

INSTRUMENT DESCRIPTION

Data recording during these Design Verification Tests (DVT) was accomplished using the following equipment:

HP 7404A Four Channel Recorder

Weston 1410 Frequency Response Analyzer

Tektronix 7603 Four Trace Oscilloscope

Fluke 8040A Digital Voltmeter

Fluke 8600A Digital Multimeter

Lebow 1228-2K Torque Transducer

Gould SC1105 Bridge Amplifier

Precision Digital 701FJ Temperature Readout

Lebow 1604-200 Torque Transducer with Tachometer Pickup

Yew 2385 -1b w/2805 Electronic Wattmeter

T & M W-4-001 Current Viewing Resistor

Pearson 110 Wideband Current Transformer

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TEST 3.3.4.1 -- OUTPUT STROKE

The output stroke was determined by using a dc input command to the EMA. The command voltage was varied to drive the EMA from full travel in one direction to full travel in the opposite direction. The EMA output motion was determined to be 13-2/3 revolutions. Since the planetary gear reducer has a gear ratio of 238.71:1, the load motion is $(13.67 \times 360)/238.71 = 20.6$ degrees. If the position offset adjustments are made to allow equal motion in either direction, this would result in the load motion being limited to about ± 10.3 degrees. This range can be changed easily by changing scaling components in the low level control circuits of the EMA.



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TEST 3.3.4.2 -- OUTPUT VELOCITY

The maximum output velocity of the EMA under no-load conditions was determined using a squarewave input command of +3 degree amplitude. Strip chart records of the input command, output motion, and tachometer outputs of the two active channels are shown in Figure 1 for a typical test. From these records it was determined that the maximum velocity of the EMA was 22.7 degrees/second.



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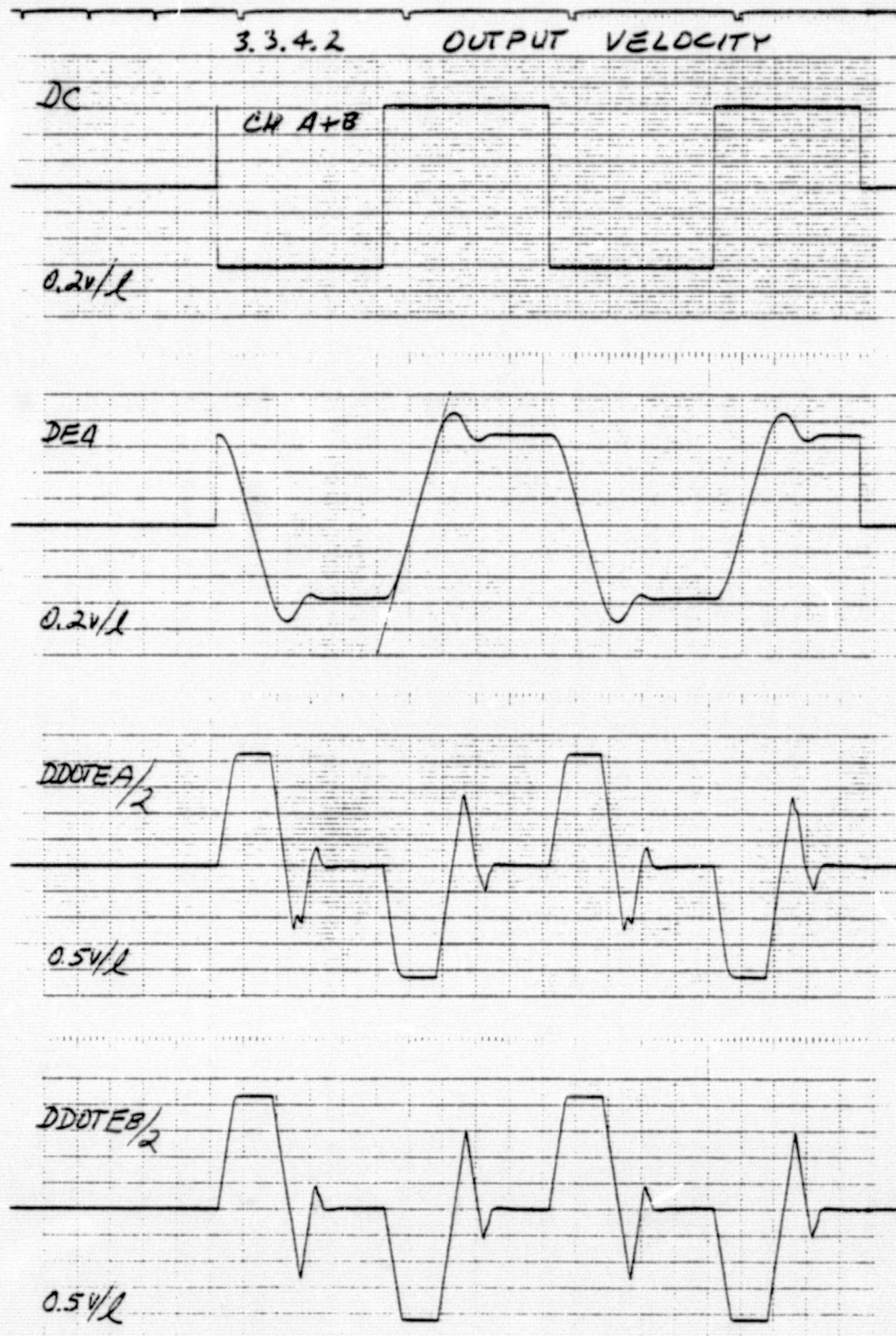


FIGURE 1. OUTPUT VELOCITY

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TEST 3.3.4.3 -- OUTPUT TORQUE

This test was conducted with the load spring connected and thermocouples mounted on the case of the motors. The first test condition was run with an 8 degree deflection and a 1 degree peak-to-peak 2.5 Hz sinusoidal excitation. The motor temperature at the beginning was 20.56 degree C and after 26 minutes had risen to 44.44 degree C. (This temperature rise was well within the design limits.) The second test condition involved a 6 degree deflection with a 4 degree peak-to-peak 1 Hz sinusoidal excitation. Beginning motor temperature was 21.11 degree C and after 5.5 minutes had risen to 33.3 degree C. The third test condition was also run with a 6 degree deflection but with a 1.27 Hz sinusoidal peak-to-peak excitation of 4 degrees. After running for 1.5 minutes the temperature had risen from 21.11 degree C to 24.44°C.

With regard to peak power represented by these tests the three test conditions were conducted at different operating points and hence different peak power.

The peak power calculation for the first condition is:

$$P = T\dot{\theta}$$

$$T = K\theta$$

$$\theta = \theta_0 + A \sin \omega t$$

$$\dot{\theta} = A\omega \cos \omega t$$

$$P = K(\theta_0 + A \sin \omega t)(A\omega \cos \omega t)$$

$$P = (K\theta_0 A\omega) \cos \omega t + \frac{KA^2\omega}{2} \sin 2\omega t$$

Parameters for condition I:

$$K = 15009.8 \frac{\text{in-lbs}}{\text{deg}}$$

$$A = 1 \text{ deg}$$

$$\omega = 15.708 \text{ rad/sec}$$

$$\theta_0 = 8 \text{ deg}$$

$$P_I = 4.988 \cos \omega t + 0.3116 \sin 2\omega t$$

$$P_I = 5.03 \text{ hp (peak)}$$



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Parameters for condition II:

$$K = 15009.8 \frac{\text{in-lbs}}{\text{deg}}$$

$$A = 4 \text{ deg}$$

$$w = 6.2832 \text{ rad/sec}$$

$$\theta_o = 6 \text{ deg}$$

$$P_{II} = 5.985 \cos wt + 3.9897 \sin 2 wt$$

$$P_{II} = 6.95 \text{ hp (peak)}$$

Parameters for condition III:

$$K = 15009.8 \frac{\text{in-lbs}}{\text{deg}}$$

$$A = 4 \text{ deg}$$

$$w = 7.98 \text{ rad/sec}$$

$$\theta_o = 6 \text{ deg}$$

$$P_{III} = 7.6 \cos wt + 5.067 \sin 2 wt$$

$$P_{III} = 11 \text{ hp (peak)}$$



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TEST 3.3.4.4 -- DISPLACEMENT LINEARITY

The displacement linearity tests were conducted using a dc input command to the EMA. The EMA output shaft was commanded to rotate in steps of one revolution, from maximum deflection in one direction to maximum deflection in the opposite direction. The output rotation was controlled to line up a mark on the EMA output shaft with a datum point. It is estimated that this was accomplished with an accuracy of about $\pm 5^{\circ}$. Since the planetary gear reducer has a ratio of 238.71:1, one revolution of the EMA output shaft corresponds to a load deflection of $360/238.71 = 1.508$ degrees. The estimated accuracy of $\pm 5^{\circ}$ in aligning the EMA output shaft would represent about ± 0.02 deg at the load. At each revolution, readings were taken of the command voltage, each of the four EMA output potentiometers (read out at the buffer amplifier outputs, A22-7), and the load deflection output voltage (at the DE amplifier, G2-7). The voltage readings were taken with a digital voltmeter. The measurements are summarized in Table 1. Figure 2 is a plot of the measured output of the EMA position feedback amplifier (DE) as a function of the EMA output shaft motion. It is evident that this voltage is a very linear function of the output motion. To check the linearity of the output voltage against the input command, calculations were made (see Table 2) by placing a straight line through the coordinates of the points recorded for the first and 13th revolutions of the EMA output shaft. From the table it can be seen that the greatest deviation was 0.066 Volts. Since the scaling is such that 1 Volt corresponds to 1 degree of load motion, this deviation would correspond to 0.066 degrees at the load. The deviation expressed in percentage of full travel (55°) is therefore

$$(0.066 \times 100)/55 = 0.12\%$$

Since the design goal for linearity is 1%, the EMA is well within the desired linearity. It should be noted that a more sophisticated method for fitting the straight line to the data (such as a least squares fit) would result in a reduced deviation measurement. As a matter of interest, similar calculations



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INPUT VOLTAGE	OUTPUT VOLTAGES					EMA SHAFT REVOLUTIONS
	POT A	POT B	POT C	POT D	DE	
+10.060	10.743	10.108	10.785	10.612	10.523	Max CCW
8.556	9.219	8.558	9.304	9.163	9.017	1 rev
7.057	7.717	7.052	7.838	7.643	7.524	2 rev
5.534	6.190	5.557	6.343	6.076	6.006	3 rev
4.074	4.702	4.133	4.904	4.594	4.553	4 rev
2.556	3.112	2.578	3.375	3.082	3.011	5 rev
1.037	1.576	1.070	1.854	1.563	1.496	6 rev
0.004	0.594	0.130	0.891	0.612	0.541	6-3/4 rev
-0.436	0.044	-0.362	0.414	0.125	0.040	7 rev
-1.954	-1.535	-1.898	-1.056	-1.386	-1.473	8 rev
-3.492	-3.026	-3.372	-2.507	-2.791	-2.918	9 rev
-5.019	-4.625	-4.931	-4.090	-4.371	-4.493	10 rev
-6.529	-6.151	-6.472	-5.673	-5.898	-6.035	11 rev
-8.027	-7.608	-7.880	-7.114	-7.347	-7.466	12 rev
-9.525	-9.189	-9.367	-8.605	-8.907	-8.994	13 rev
-10.527	-10.232	-10.407	-9.613	-10.504	-10.501	13-2/3 rev

TABLE 1 . EMA INPUT AND OUTPUT VOLTAGES AS A FUNCTION
OF EMA OUTPUT SHAFT ROTATION

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MEASURED EMA POSITION FEEDBACK SENSOR OUTPUT (VOLTS)

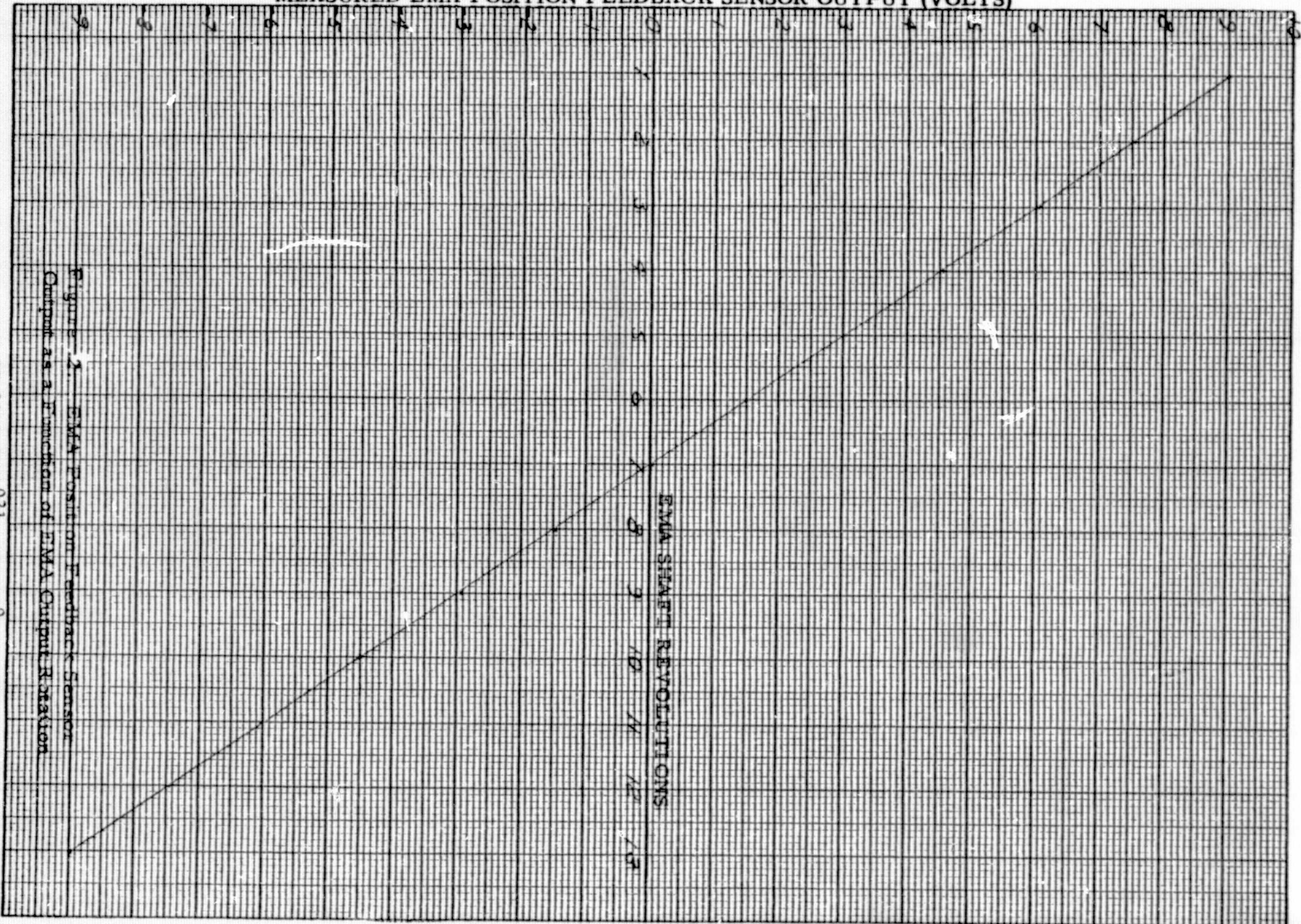


Figure 2. EMA Position Feedback Sensor Output as a Function of EMA Output Rotation



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were conducted for each of the output potentiometers. These are summarized in Tables 3 through 6. Calculations were also made to determine the maximum deviation from the straight line fitted to the data for each of these outputs. Table 7 summarizes these calculations and also presents the average deviation and the RMS deviation for each of the outputs. Pot C had the largest maximum deviation (0.22% of full travel) and also had the largest average deviation (0.048% of full travel). However, Pot D had the largest RMS deviation (0.103% of full travel).

A linear regression method was also used to establish a straight line to fit the data of Table 2. The least squares fitting provided a slight improvement in the deviations for DE. A comparison with the data of Table 7 showed that the maximum deviation went from 0.12% to 0.11%, the average deviation was reduced from 0.0002% to 0.000%, and the RMS deviation changed from 0.054% to 0.053%.



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INPUT VOLTAGE X	STRAIGHT LINE ORDINATE Y	MEASURED OUTPUT DE	DEVIATION
8.556	9.017	9.017	0.000
7.057	7.524	7.524	0.000
5.534	6.007	6.006	0.001
4.074	4.552	4.553	-0.001
2.556	3.040	3.011	0.029
1.037	1.527	1.496	0.031
0.004	0.498	0.541	-0.043
-0.436	0.060	0.040	0.020
-1.954	-1.452	-1.473	0.021
-3.492	-2.984	-2.918	-0.066
-5.019	-4.505	-4.493	-0.012
-6.529	-6.010	-6.053	0.043
-8.027	-7.502	-7.466	-0.036
-9.525	-8.994	-8.994	0.000

TABLE 2 . DEVIATION CALCULATIONS FOR DE



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<u>INPUT VOLTAGE X</u>	<u>STRAIGHT LINE ORDINATE Y</u>	<u>MEASURED OUTPUT POT A</u>	<u>DEVIATION</u>
8.556	9.219	9.219	0.000
7.057	7.693	7.717	-0.024
5.534	6.142	6.190	-0.048
4.024	4.656	4.702	-0.046
2.556	3.110	3.112	-0.002
1.037	1.564	1.576	-0.012
0.004	0.512	0.594	-0.082
-0.436	0.064	0.044	0.020
-1.954	-1.481	-1.535	0.054
-3.492	-3.047	-3.026	-0.021
-5.019	-4.602	-4.625	0.023
-6.529	-6.139	-6.151	0.012
-8.027	-7.664	-7.608	-0.056
-9.525	-9.189	-9.189	0.000

TABLE 3 . DEVIATION CALCULATIONS FOR POT A



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<u>INPUT VOLTAGE X</u>	<u>STRAIGHT LINE ORDINATE Y</u>	<u>MEASURED OUTPUT POT B</u>	<u>DEVIATION</u>
8.556	8.558	8.558	0.000
7.057	7.072	7.052	0.020
5.534	5.562	5.557	0.005
4.074	4.115	4.133	-0.018
2.556	2.610	2.578	0.032
1.037	1.104	1.070	0.034
0.004	0.080	0.130	-0.050
-0.436	-0.356	-0.362	0.006
-1.954	-1.861	-1.898	0.037
-3.492	-3.386	-3.372	-0.014
-5.019	-4.900	-4.931	0.031
-6.529	-6.397	-6.472	0.075
-8.027	-7.882	-7.830	-0.002
-9.525	-9.367	-9.367	0.000

TABLE 4 . DEVIATION CALCULATIONS FOR POT B



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<u>INPUT VOLTAGE X</u>	<u>STRAIGHT LINE ORDINATE Y</u>	<u>MEASURED OUTPUT POT C</u>	<u>DEVIATION</u>
8.556	9.304	9.304	0.000
7.057	7.819	7.838	-0.019
5.534	6.311	6.343	-0.032
4.074	4.865	4.904	-0.039
2.556	3.361	3.375	-0.014
1.037	1.857	1.854	0.003
0.004	0.833	0.891	-0.058
-0.436	0.398	0.414	-0.016
-1.954	-1.106	-1.056	-0.050
-3.492	-2.629	-2.507	-0.122
-5.019	-4.142	-4.090	-0.052
-6.529	-5.638	-5.673	0.035
-8.027	-7.121	-7.114	-0.007
-9.525	-8.605	-8.605	0.000

TABLE 5 . DEVIATION CALCULATIONS FOR POT C



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<u>INPUT VOLTAGE X</u>	<u>STRAIGHT LINE ORDINATE Y</u>	<u>MEASURED OUTPUT POT D</u>	<u>DEVIATION</u>
8.556	9.163	9.163	0.000
7.057	7.665	7.643	0.022
5.534	6.143	6.076	0.067
4.074	4.684	4.594	0.090
2.556	3.167	3.082	0.085
1.037	1.649	1.563	0.086
0.004	0.616	0.612	0.004
-0.436	0.176	0.125	0.051
-1.954	-1.341	-1.386	0.045
-3.492	-2.878	-2.791	-0.087
-5.019	-4.404	-4.371	-0.033
-6.529	-5.913	-5.898	-0.015
-8.027	-7.410	-7.347	-0.063
-9.525	-8.907	-8.907	0.000

TABLE 6 . DEVIATION CALCULATIONS FOR POT D

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MEASURED DEVIATIONS (IN PERCENT OF FULL TRAVEL)

<u>OUTPUT</u>	<u>MAXIMUM DEVIATION</u>	<u>AVERAGE DEVIATION</u>	<u>ROOT MEAN SQUARE DEVIATION</u>
POT A	0.15%	0.024%	0.068%
POT B	0.14%	0.020%	0.057%
POT C	0.22%	0.048%	0.081%
POT D	0.16%	0.033%	0.103%
DE	0.12%	0.002%	0.054%

TABLE 7 . DEVIATIONS FROM STRAIGHT LINE
THROUGH MEASURED END POINTS



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TEST 3.3.4.5 -- THRESHOLD

The threshold of the EMA was demonstrated to be less than 0.05% of full travel, using a 0.01 Hz sinusoidal input command with an amplitude of 0.0275 Volts (corresponding to 0.0275 degrees, or 0.5% of the system's 55 degree full travel). A strip chart record showing the input command and the output motion is given in Figure 3. From this record, output motion is clearly evident, demonstrating that the threshold is less than 0.05% of full travel.

Additional runs were made with an input command amplitude of 0.00275 degrees (0.005% of full travel). All six channel combinations were tested. Three combinations (AB, AD, and CD) responded to the input and the other three did not.



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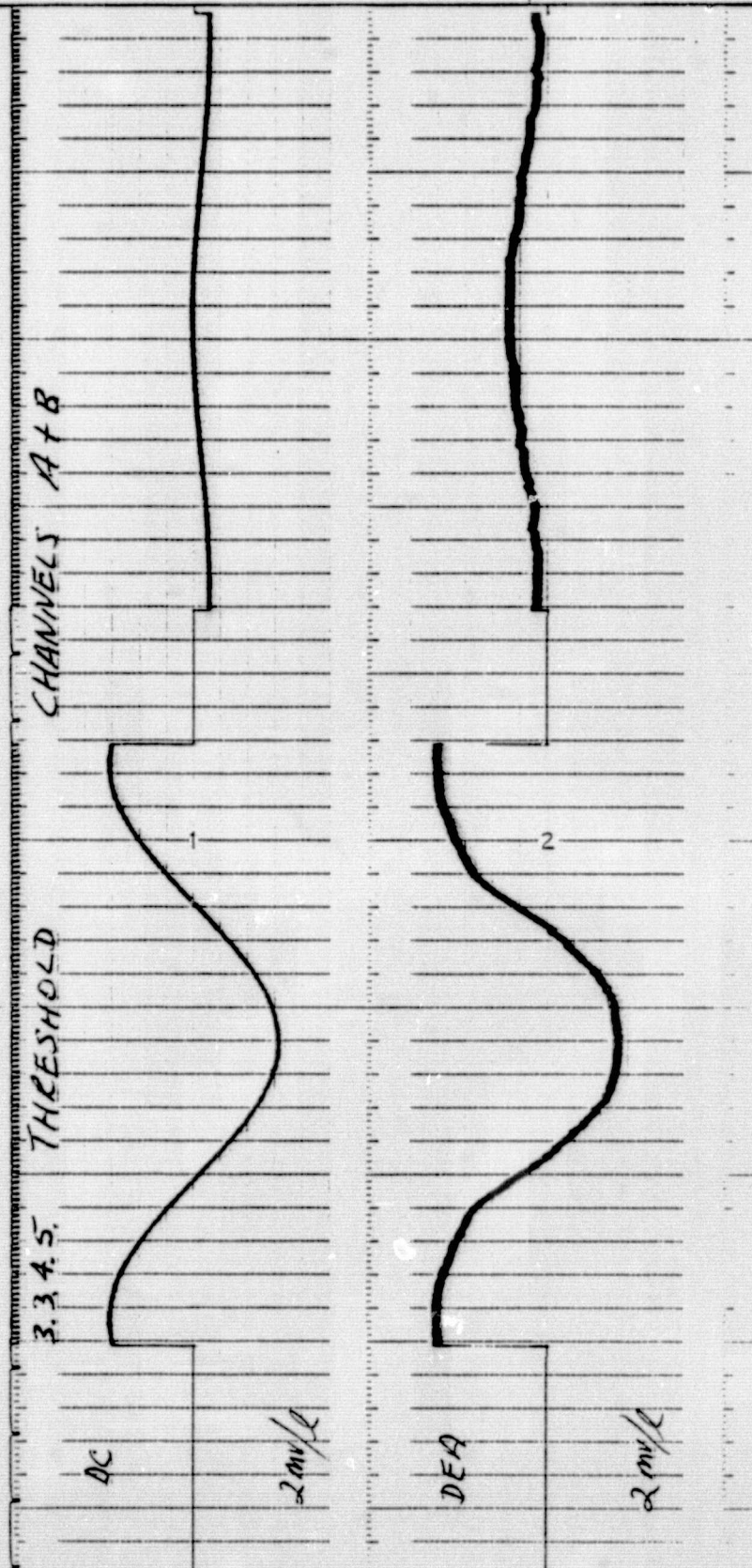


FIGURE 3 THRESHOLD

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3.3.4.6 POSITION NULL

EMA output position null is determined by setting all input commands to the four channels to zero and recording the output position. Table 8 indicates that the inputs to each channel were driven to very nearly zero and the resulting offset was 0.0186 degrees. The requirement is for less than 0.275 degrees. This requirement is easily met. The other requirement is that each offset adjust potentiometer be capable of driving the EMA output ± 2.75 degrees. Table 8 shows that each channel met this requirement. (Channel C was inoperative during this test as a result of Q_M switch failing shorted.)

For the first part of the test all four channels were active. The remaining offset measurements were conducted with only one channel at a time activated to produce the EMA deflection. The active channel for each test has the offset voltage listed.



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POSITION OFFSET ADJUST

CHANNEL A	CHANNEL B	CHANNEL C	CHANNEL D	EMA OUTPUT DE
<u>VOLTS</u>	<u>VOLTS</u>	<u>VOLTS</u>	<u>VOLTS</u>	<u>DEGREES</u>
- .0075	+.0074	+.0039	-.0062	+0.0186
+12.144				-3.129
-12.095				+3.149
	+12.145			-3.018
	-12.098			+3.037
			+12.136	-3.062
			-12.088	+3.090

TABLE 8 POSITION NULL RESULTS



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3.3.4.7 -- HYSTERESIS

The hysteresis plot was made on the oscilloscope with a single trace time exposed picture.

Both the input and output to the EMA were filtered with a low pass ($f = 0.114$ Hz) to eliminate signal noise. The input was a 0.01 Hz sinusoidal waveform with a 110 mV (0.11 degree) peak-to-peak amplitude. Channels B + D exhibited very little hysteresis (see Figure 4) whereas Channels C + D exhibited 8 mV (.008 degrees) of hysteresis. For all motor combinations the measured hysteresis for all combinations of channels fell comfortably below the limit of 27.5 mV (.0275 degrees).



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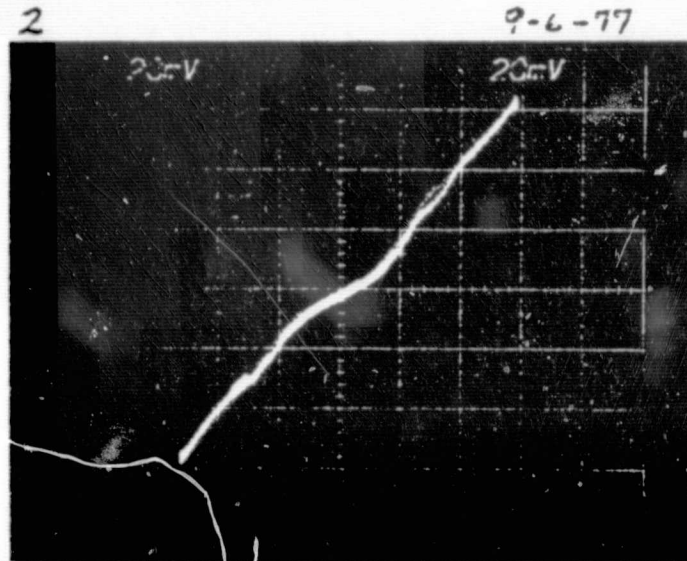
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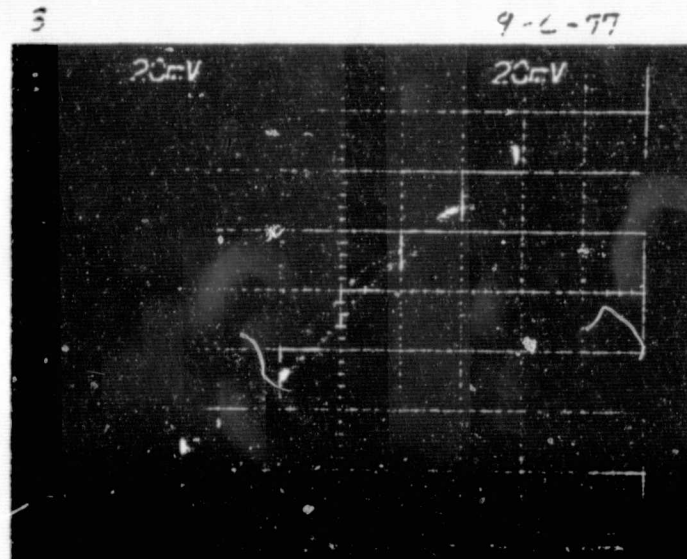
OUTPUT
MOTION
DE



CHANNELS
B AND D
ACTIVE

INPUT COMMAND, DC

OUTPUT
MOTION
DE



CHANNELS
C AND D
ACTIVE

INPUT COMMAND, DC
FIGURE 4 HYSTERESIS

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3.3.4.8 CROSS-CHANNEL VELOCITY TRACKING

All six combinations of motors were tested for their velocity tracking error. A triangular waveform of ± 10 degree command at 0.43 Hz (± 17.4 deg/sec command rate) was used for excitation. Results of two of the motor combinations can be seen in Figure 5. Velocity tracking requirements are that the error shall not exceed 3% of full velocity which is 0.7 deg/sec at the output or 290 rpm at the motor.

From Figure 5 it can be seen that the velocity error has a large transient when the command waveform changes from motion in one direction to the opposite. With motors A and D active, the positive velocity error just prior to the transient is

$$(1 \text{ line})(0.05 \text{ V/line})(4 \text{ deg/sec-V}) = 0.2 \text{ deg/sec}$$

In terms of full velocity (23 deg/sec), this is an error of

$$0.2 \times 100/23 = 0.9\%$$

The negative velocity error is found to be 0.1 deg/sec, which corresponds to 0.4% of full velocity. Channel combination AD is therefore well within the 3% velocity tracking error design goal.

Similar calculations for the other channels gave the following results:

<u>Channel</u> <u>Combination</u>	<u>Velocity Tracking Errors</u>	
	<u>Positive</u>	<u>Negative</u>
AB	+3.0%	-1.3%
AC	+1.3	+0.4
AD	+0.9	-0.4
BC	+2.6	-2.6
BD	+2.6	-2.2
CD	+0.4	-0.4



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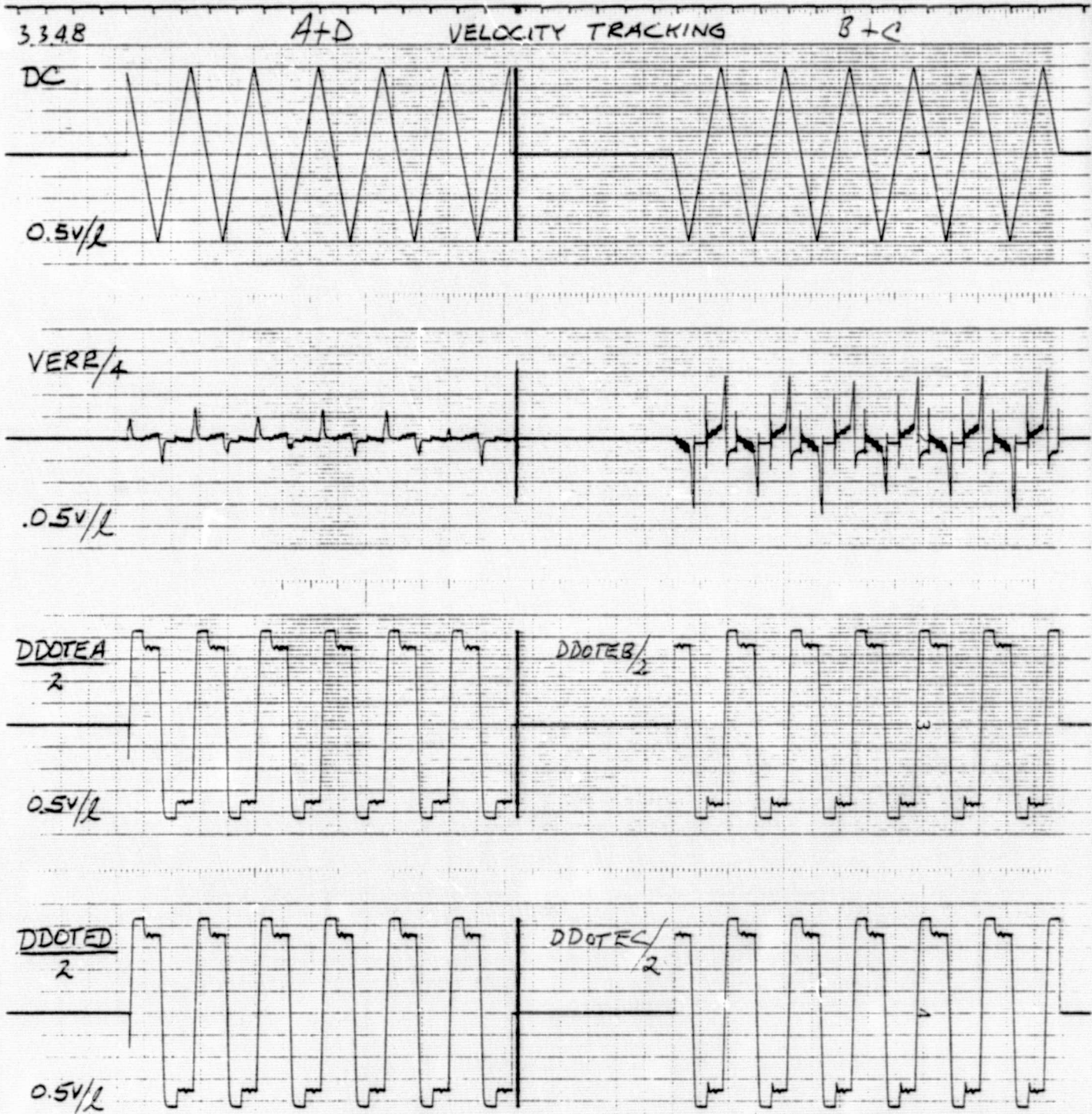


FIGURE 5 VELOCITY TRACKING

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3.3.4.9 -- FREQUENCY RESPONSE

All six motor combinations were tested for their closed loop frequency response. Figures 6 and 7 represent a typical set of response curves. For convenience the gain and phase boundaries are plotted on the responses to show compliance with the SOW. The remaining 5 motor combinations also met these requirements and furthermore were nearly identical in performance. All six combinations tested exhibited between 8 and 9 Hz bandwidth (-1db).



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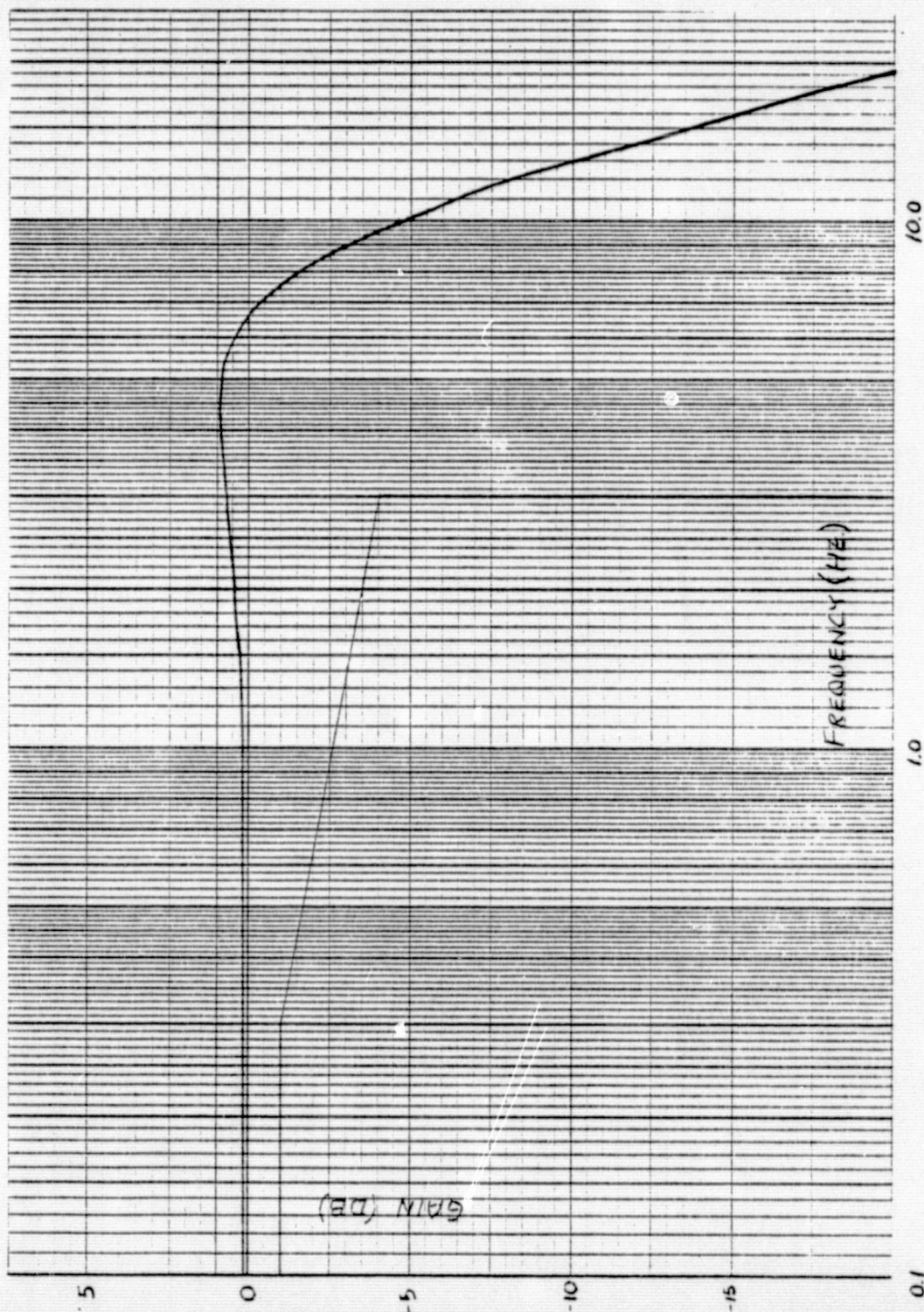


FIGURE 6 EMA FREQUENCY RESPONSE

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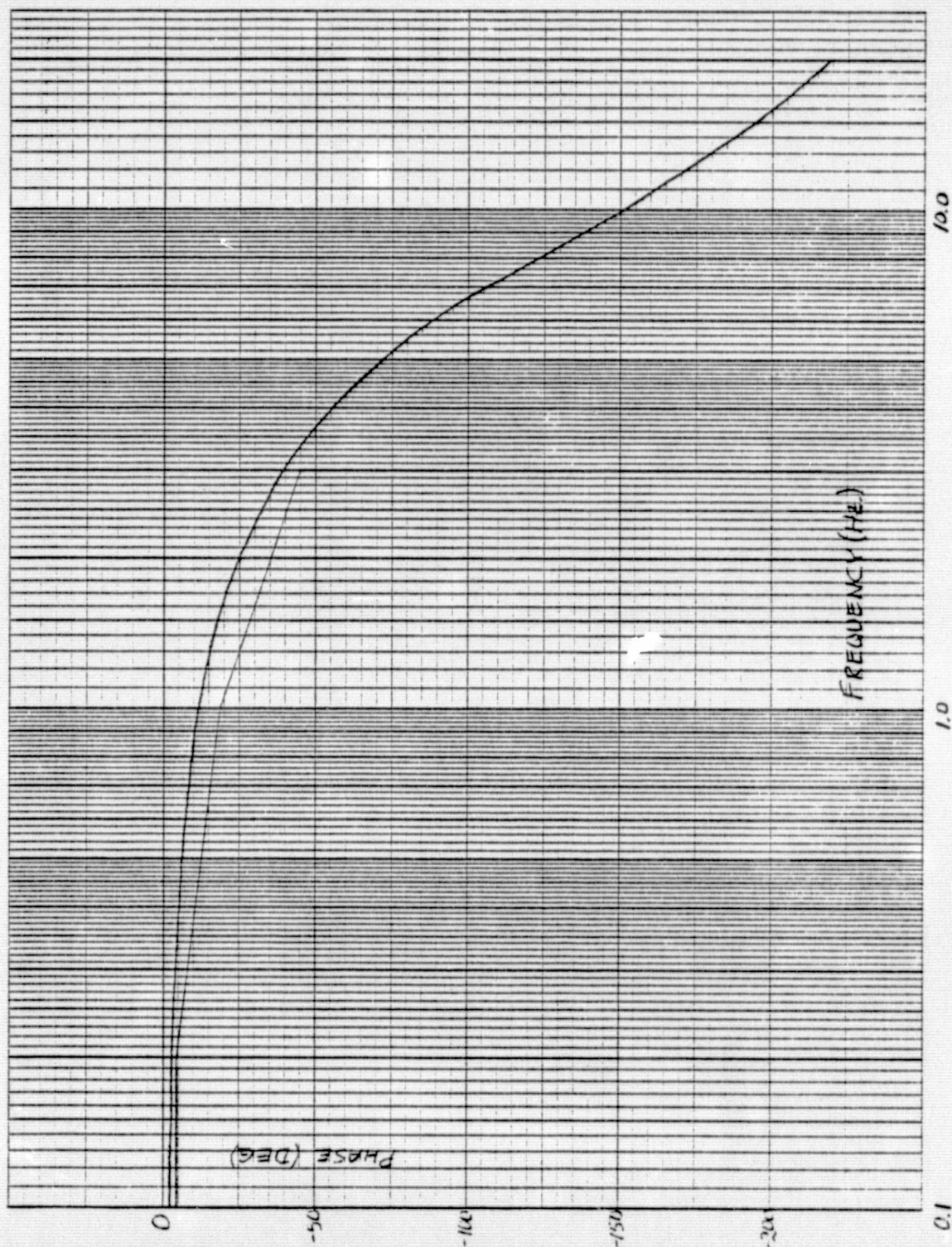


FIGURE 7 EMA FREQUENCY RESPONSE



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3.3.4.10 STEP RESPONSE

Closed loop step responses were run for all six motor combinations with four inputs of +2%, +3%, +4% and +5% of full travel. Typical results of these tests are shown in Figures 8 through 11. To aid in the interpretation the step response design goal boundaries are plotted over each EMA output response.

With a 2% step input, the response (see Figure 8) is within the design goal envelope, although the maximum overshoot equals the allowable value (25%). For a 3% step input, the overshoot in the response slightly exceeds the design goal (30% overshoot vs the 25% design goal).

With a 4% step input command, the response is essentially within the design goal envelope (the overshoot for this condition is about 27%). For a 5% step input, the overshoot is about 22%, but the time required to reach 85% of the steady-state response exceeds the design goal by about 14%.

These responses were run with the load spring connected. Similar results were obtained when the load spring was disconnected.

For inputs of less than ± 0.5% FT, torque saturation is not present and the EMA response consistently meets design goals.



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3.3.4.10 STEP RESPONSE (WITH LOAD)

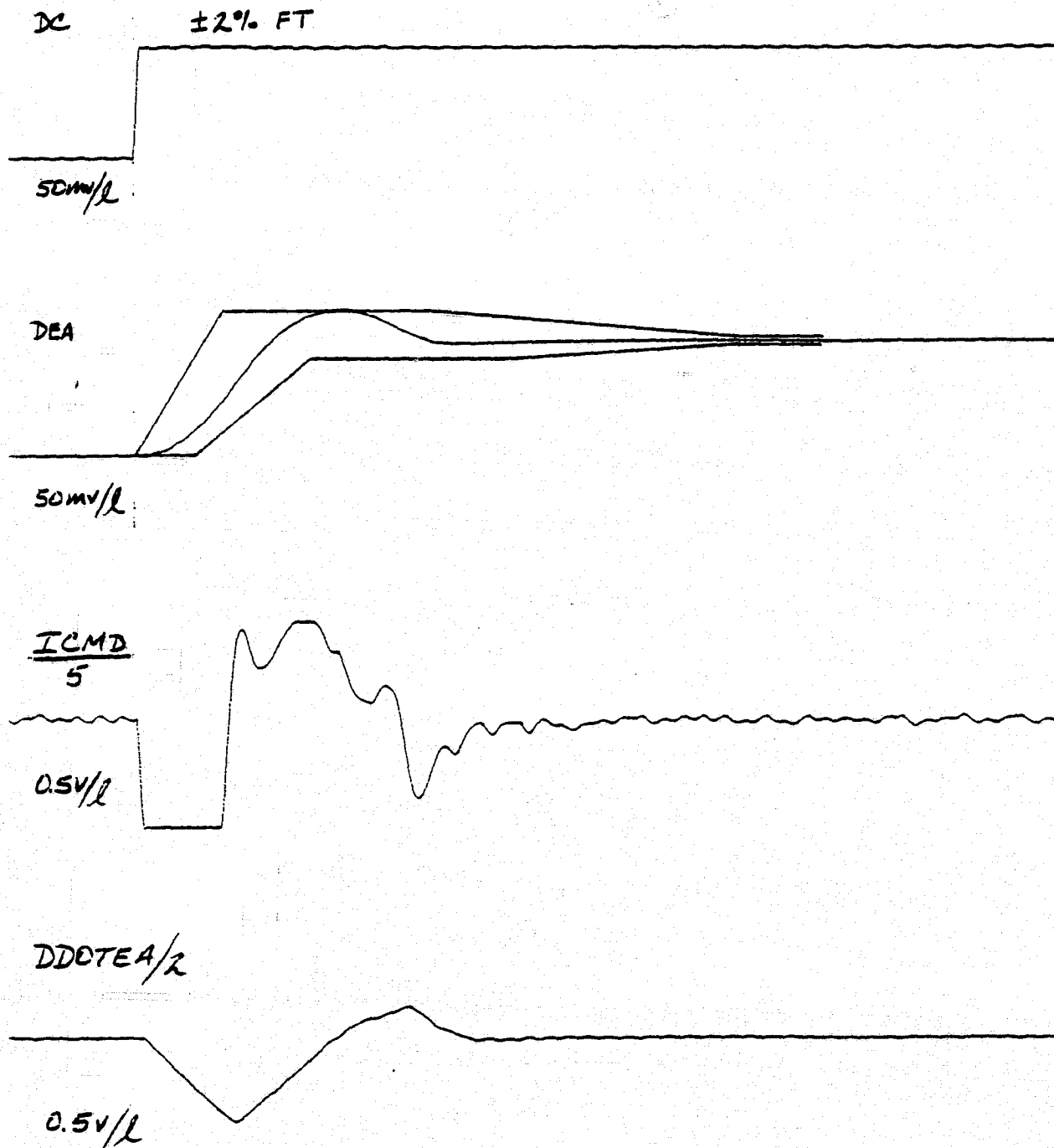


FIGURE 8 STEP RESPONSE



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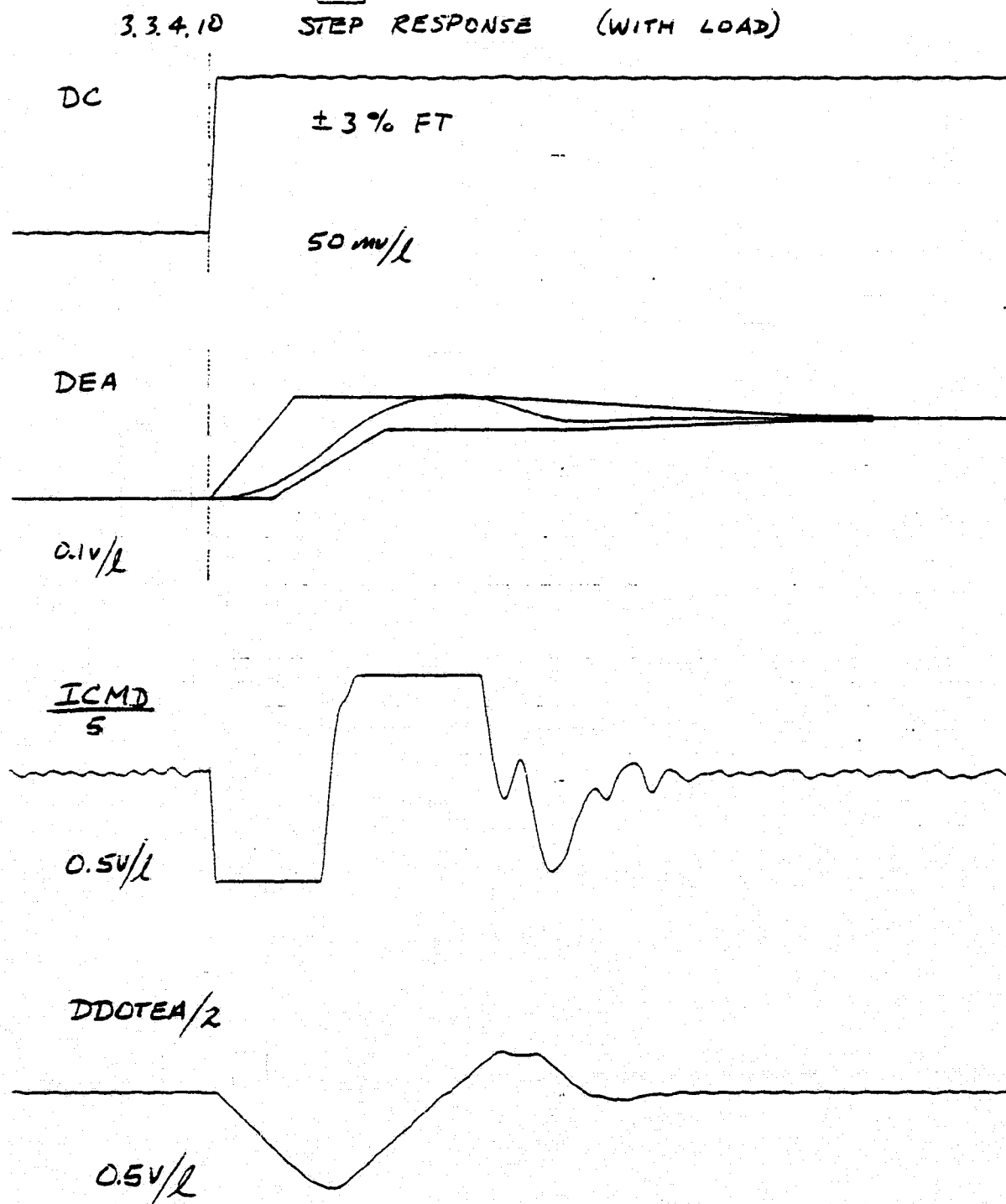
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FIGURE 9 STEP RESPONSE



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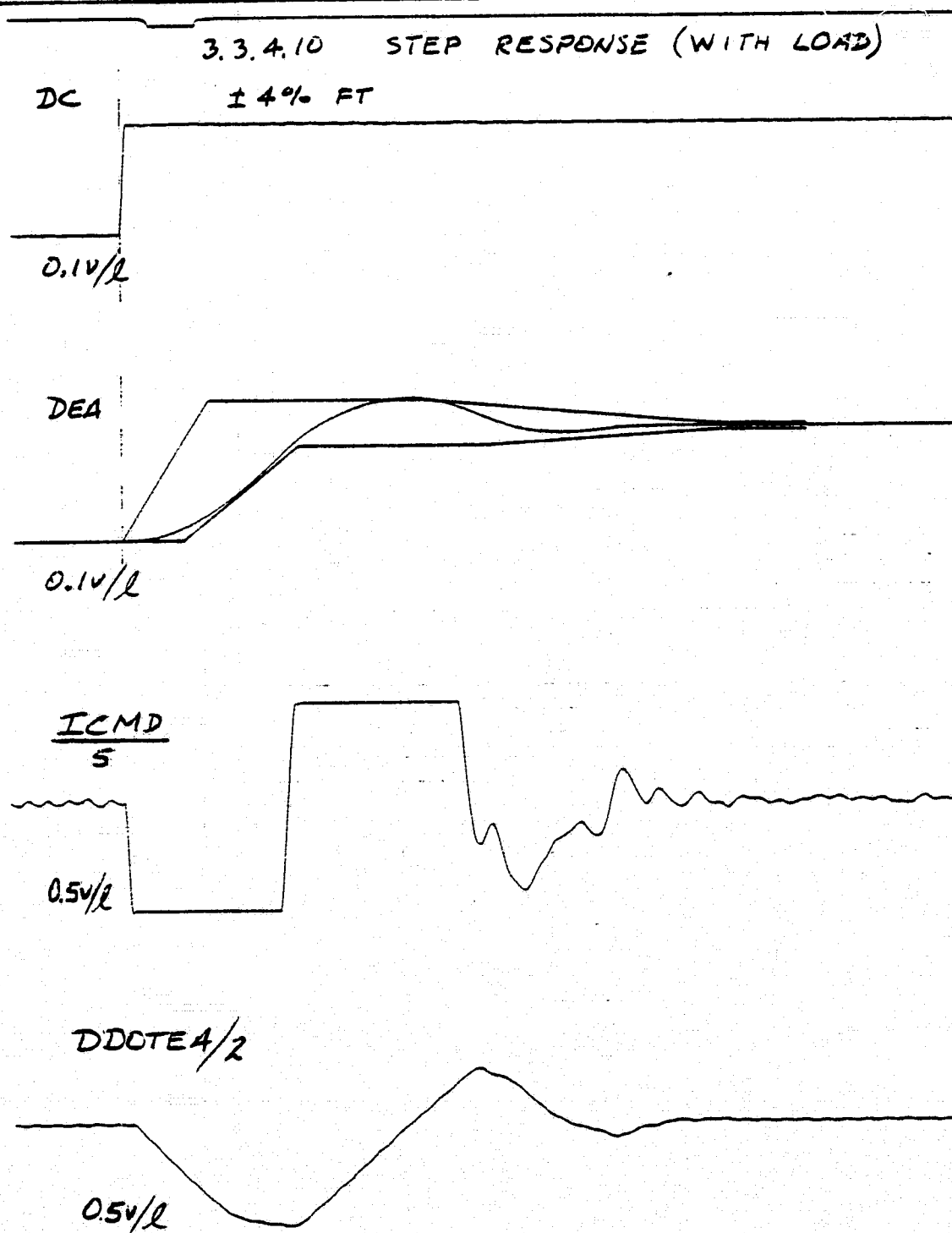


FIGURE 10 STEP RESPONSE



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3.3.4.10 STEP RESPONSE (WITH LOAD)

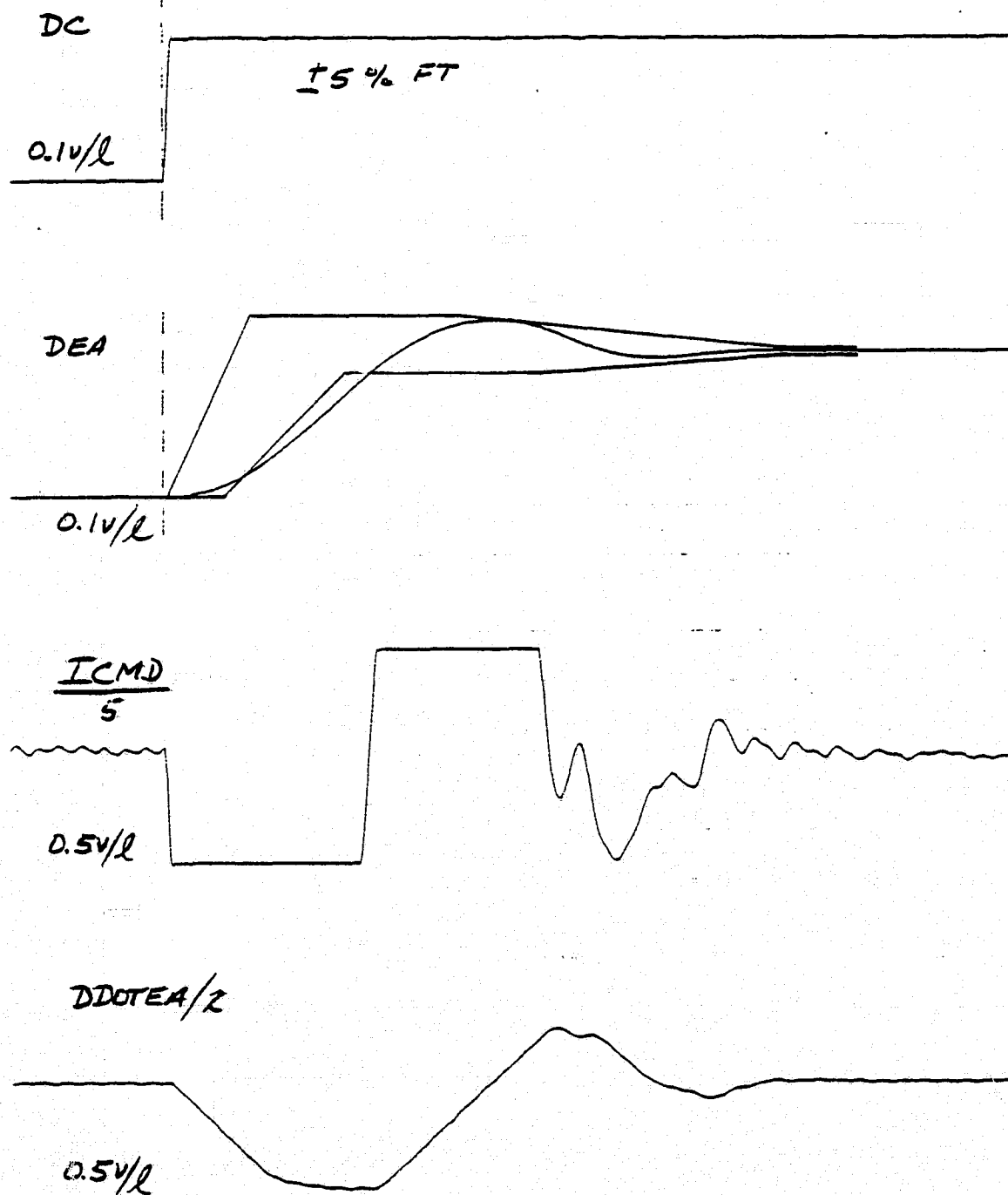


Figure 11 STEP RESPONSE



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3.3.4.11 -- MOTOR BRAKE

The EMA output shaft was locked during this test. One at a time, each motor was operated at its full output torque to test the braking torque of the three remaining brakes. All four tachometer signals were recorded at high sensitivities to observe any slippage that might occur. Figures 12 and 13 show stripchart records of the data taken during these tests. During the first interval, channel A was active. The tachometer output from channel B showed no motion for positive torque, and a small spike showing a slight motion when negative torque was first commanded. Channel C showed slight motion when negative torque was commanded from motor A, but no motion for positive torque. Channel D showed slight motion for both positive and negative torque commands. Even though the brakes appear to be operating effectively during this test, some backlash in the brake couplings apparently allows a very slight motion of the tachometer shafts for channels C and D.

With channel B active, no motion was detected for channels A or C, but a slight tachometer output was found for channel D, indicating that its brake coupling may have sufficient backlash to allow a small amplitude motion. With channel C active, neither channel A nor B showed any motion, but a slight movement was detected at channel D. With channel D active, no motion was detected for channels A or B, and channel C showed only a slight motion as channel D started producing negative torque.

The data taken during these tests indicate that the brakes do not slip under static braking conditions (except for a small, momentary motion which occurred in some instances when a given torque was first applied). Channel D appears to have sufficient backlash in its brake coupling to allow a measurable tachometer output, and channel C also showed similar motion with channel A applying negative torque.

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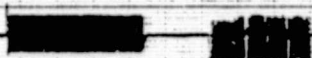
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3.3.4.11 MOTOR BRAKE

DDOTE A/2

A ACTIVE



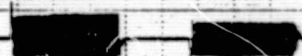
(+)

(-)

0.1V/2

DDOTE B/2

B ACTIVE



(+)

(-)

0.1V/2

DDOTE C/2



0.1V/2

DDOTE D/2

0.1V/2

FIGURE 12 MOTOR BRAKE TEST



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3.3.4.11 MOTOR BRAKE

DDOTE A/2

0.1V/L

DDOTE B/2

0.1V/L

DDOTE C/2

C ACTIVE

0.1V/L

(-)

(+)

89-14 = 3.0V

89-14 = 2.8V

DDOTE D/2

D ACTIVE

0.1V/L

(+)

(-)

89-14 = 3.06V

89-14 = 4.0

FIGURE 13 MOTOR BRAKE TEST



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3.3.4.12 -- CHATTER AND INSTABILITY

During all DVT tests EMA operation was observed for any chatter and instability that exceeded 0.055 degrees peak-to-peak at the load arms. None was observed or recorded that came close to this limit. The EMA output motion can be seen in Figures 8 through 11 and no apparent dither or instability is present.



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3.3.4.13 -- VELOCITY GAIN TEST

The velocity gain test was run with the EMA output blocked and the position loop opened. Results of the test are shown in Figure 14. The reason for the negative slope is that a full current command had to be inputted so that the current command had the correct sign. This was necessary to operate the motor in the motoring mode. If just the tachometer signal were used for an input the plugging logic limited the current to the motor to 25 amps. Calculating the slope of the velocity gain curve yields a gain of 0.035 amps/RPM. This value checks with the gains implemented in the system.



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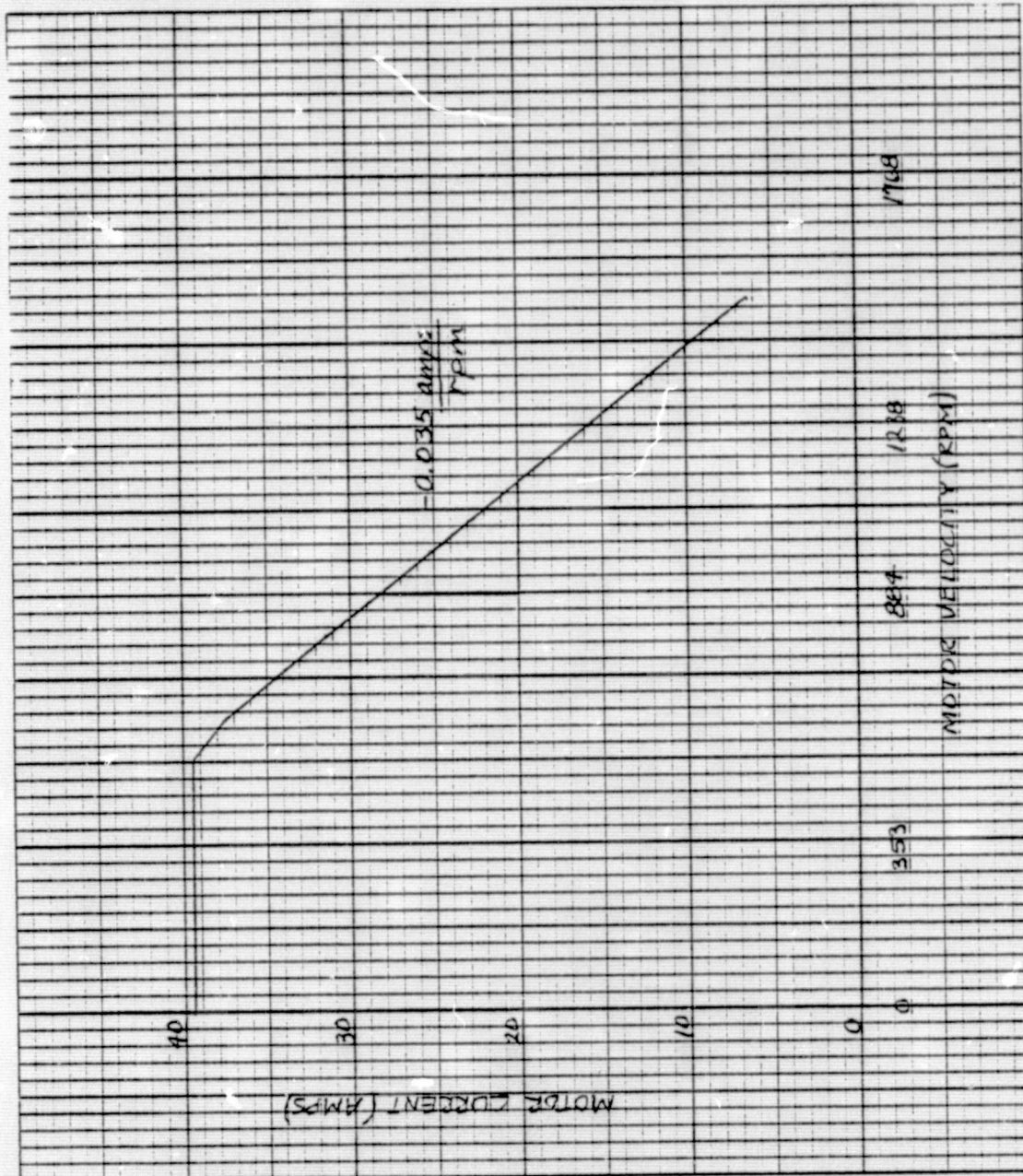


FIGURE 14 VELOCITY GAIN TEST

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3.3.4.14 -- TORQUE GAIN TEST

The torque gain test was run with the EMA output shaft locked, and with the position, tachometer and velocity comparison loops open. The input command was the position command and readings taken were current command, motor current and EMA output torque. Figure 15 depicts the results of this test. The calculated gain from the hardware comes to 425.5 Amps/deg which compares very well with the slope of the measured data.



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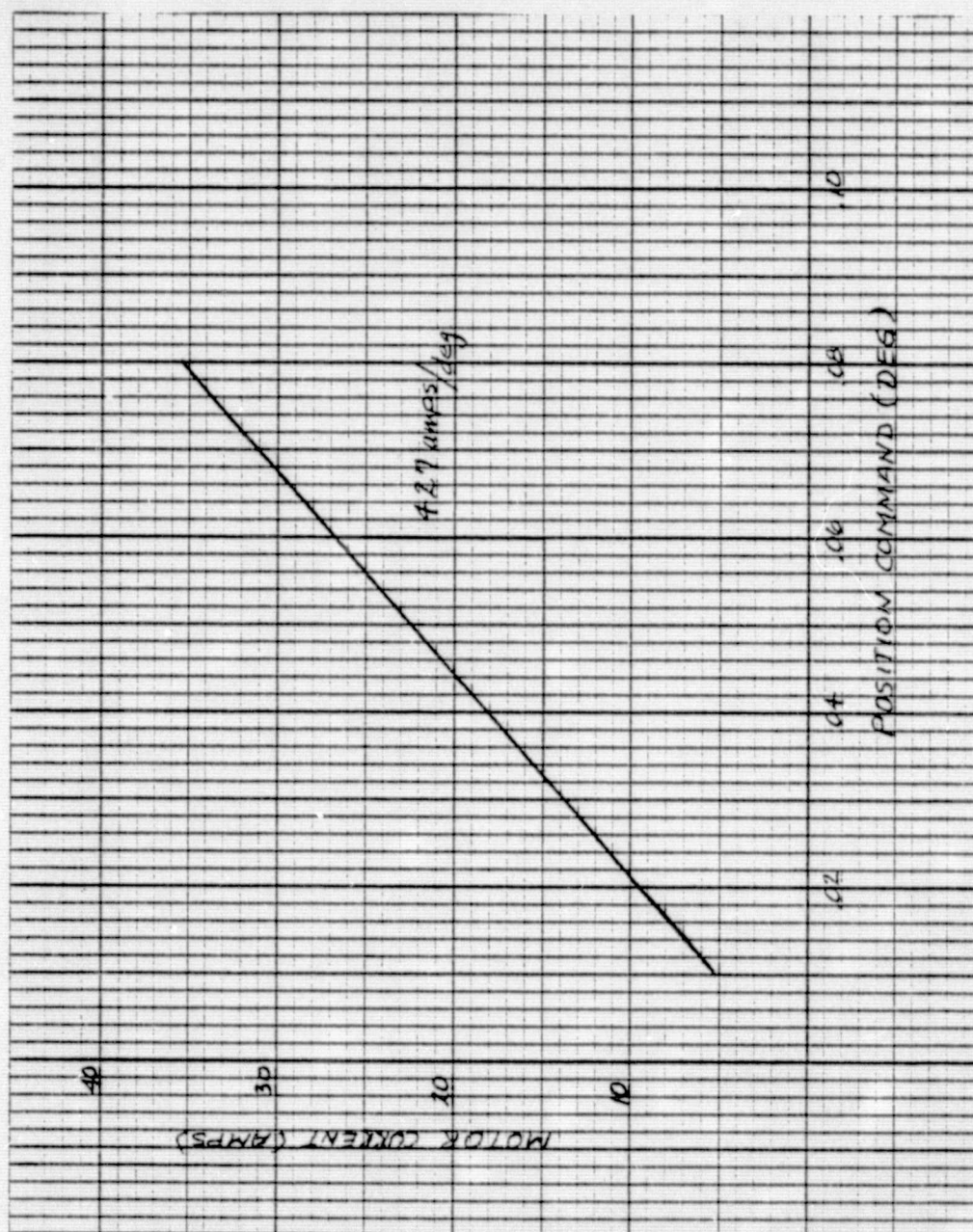


FIGURE 15. TORQUE GAIN TEST

APPENDIX K

POWER COMPONENT TESTS

This appendix contains Delco document EE-22T-EMA-022 which covers the power components tests which were conducted to aid in selecting the power transistors for use in the single-channel power electronics breadboard.



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TITLE:

POWER COMPONENT TESTS

BY:

A. Barrett/H. Hansen

APPROVED:

N. Hansen

DATE:

12/20/77

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INTRODUCTION

This report summarizes the power transistor testing which was done to select the best state-of-the-art devices for use in the single-channel power electronics breadboard. Since the EMA has a nominal 270 Vdc supply, and the idealized motor currents under rated load are 60A, 600 Hz waveforms (having the characteristics shown in Figure 1), the power transistors must have large voltage and current ratings. Moreover, the chopper transistors which provide current control should be capable of handling full motor currents while operating at 8 kHz with an 80% on-time duty cycle. The switching characteristics of candidate devices were therefore of major importance, in addition to the critical voltage and current rating requirements.

The requirements and design goals for the various power transistor parameters are summarized in Table 1. The V_{CEO} (SUS) requirement (400V) allows for reasonable variations in the nominal 270 Vdc supply voltage as well as transient peaks. The peak collector current requirement (100A) allows appreciable overshoot beyond the 60A nominally required by the motor to develop full output power.

A vendor survey was conducted in an attempt to find suitable power transistors. Inquiries were sent to the following manufacturers:

- o Ampower Semiconductor
- o Delco Electronics
- o Fairchild Semiconductor
- o General Electric
- o Kertron
- o Motorola Semiconductor
- o Power Physics
- o PowerTech
- o RCA Solid State
- o RSM Sensitron
- o Semicoa
- o Silicon Transistor
- o Siliconix



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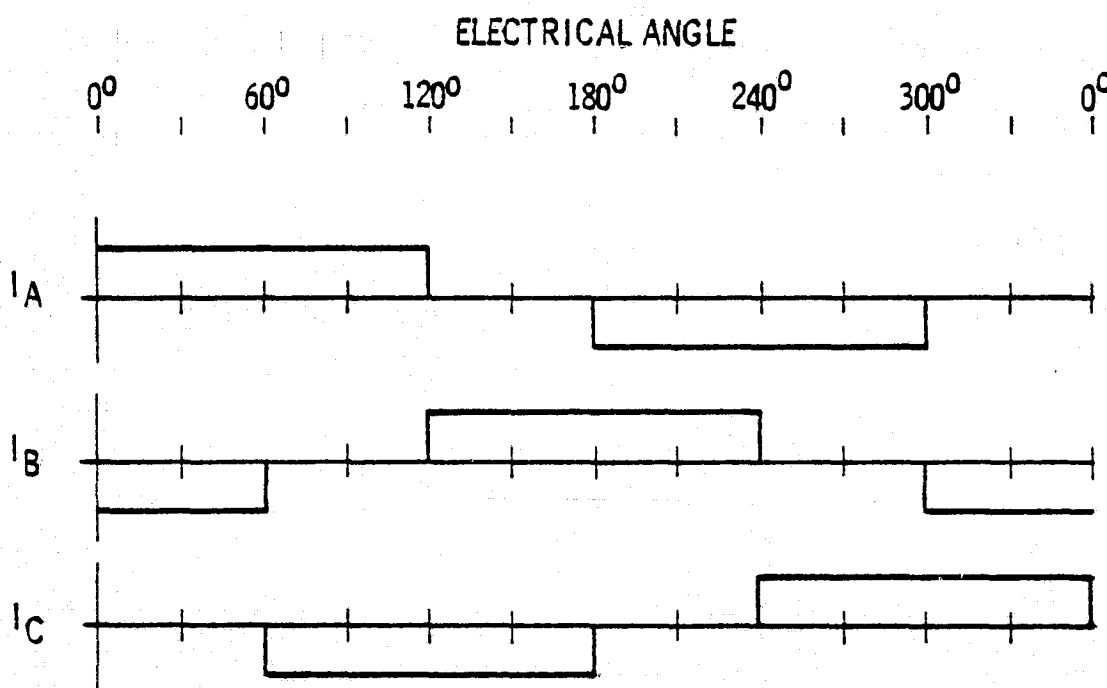


FIGURE 1. IDEALIZED MOTOR CURRENT WAVEFORMS



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<u>PARAMETER</u>	<u>REQUIREMENT</u>	<u>GOAL</u>
V_{CEO} (SUS)	400V	425V
I_C	60A	100A
I_C PEAK	100A	150A
BETA AT 60A	10 AT $V_{CE} = 1V$	15
BETA AT 100A	7.5 AT $V_{CE} = 1.5V$	10
V_{CE} (SAT)	1V AT $I_C = 60A$, $I_B = 6A$	0.5V
P_D	250W AT $T_C = 100^{\circ}C$	300W
RISE TIME	0.8 MICROSECOND	0.5
STORAGE TIME	6 MICROSECONDS	3
FALL TIME	1.2 MICROSECONDS	0.8

TABLE 1. POWER TRANSISTOR PARAMETER REQUIREMENTS
AND GOALS



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- o Solid State Devices
- o Solitron Devices
- o Texas Instruments
- o Transitron Electronic
- o TRW Semiconductor
- o Westinghouse Electric

The available data sheets for candidate transistors were examined, and it was determined that several devices had potentially acceptable characteristics. The devices which were selected for further test and evaluation were:

- o Westinghouse developmental unit 17B-X
(predecessor to type D60T)
- o RCA type J15490 (transcendent device)
- o PowerTech type PT-4503
- o Delco type DTS-4075

The tests which were conducted on the candidate transistors are summarized in the following paragraphs.

TEST METHODS

The power transistors were tested using the circuit shown in Figure 2. The basic load consists of a resistor, R_L , and an inductor, L . The inductor is the same as that used as the current source in the EMA power converter. The snubber circuit which is shown in Figure 2 is one of a number of configurations that were evaluated during the tests. Alternate snubber configurations (as well as the one shown in Figure 2) are shown in Figures 3 through 6.

During the initial evaluation it was determined that the snubber configuration designated A6 was the most suitable of those considered. In the actual EMA power converter the transistors used in the inverter are series-connected. For this reason, the more complex snubbers shown in Figures 4 through 6 are not practical, even though each has certain advantages when considered for use with a single transistor. Since the battery provides a relatively stiff voltage source for the EMA power converter, snubber configuration A6 is the equivalent of a snubber network having 20 Ohms in series with 0.125 microfarad used as a snubber by each of the two series-connected transistors.

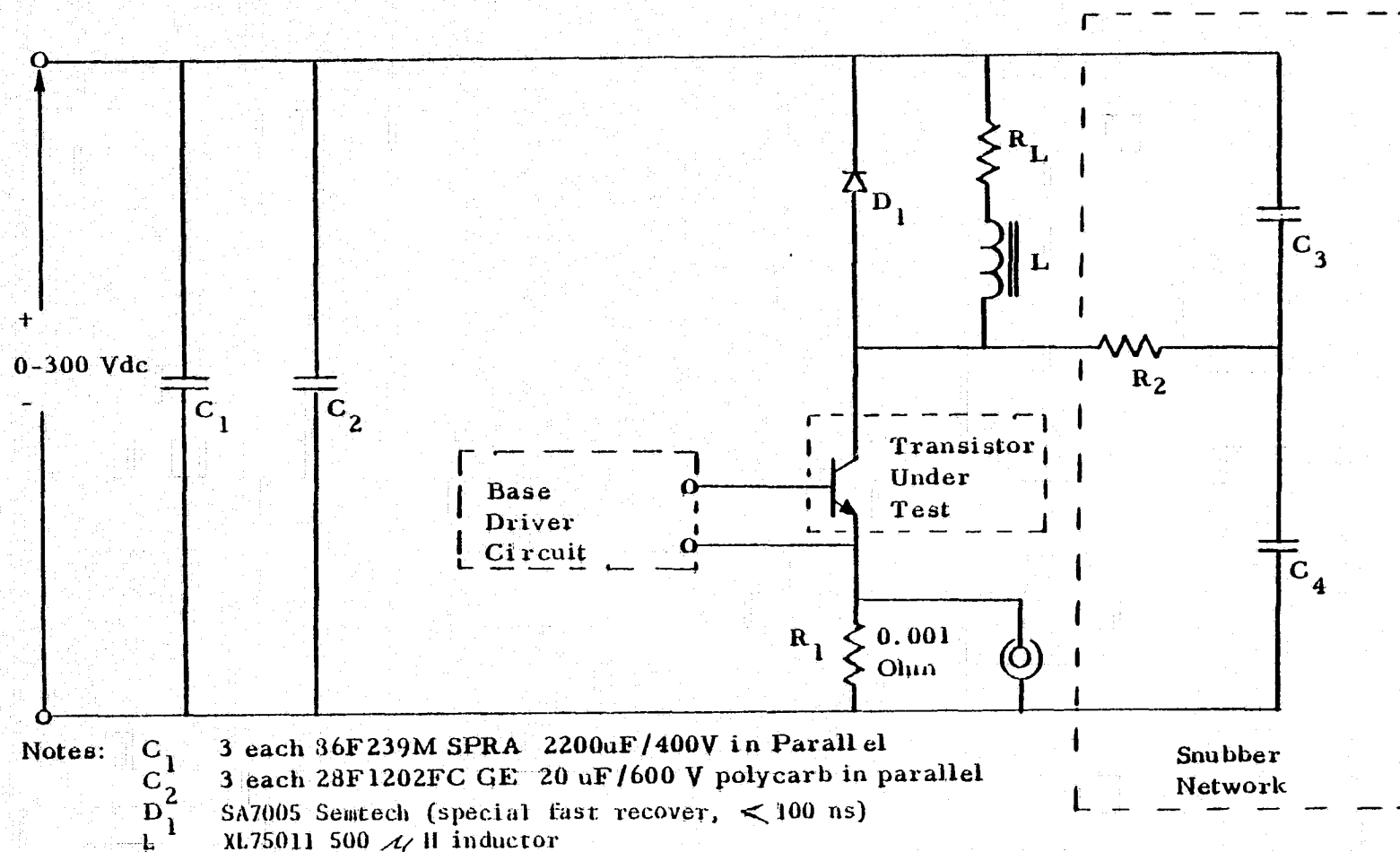


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Notes: C₁ 3 each 36F239M SPRA 2200uF/400V in Parallel
C₂ 3 each 28F1202FC GE 20 uF/600 V polycarb in parallel
D₁ SA7005 Semtech (special fast recover, < 100 ns)
L XL75011 500 μ H inductor

Figure 2. Basic Test Circuit



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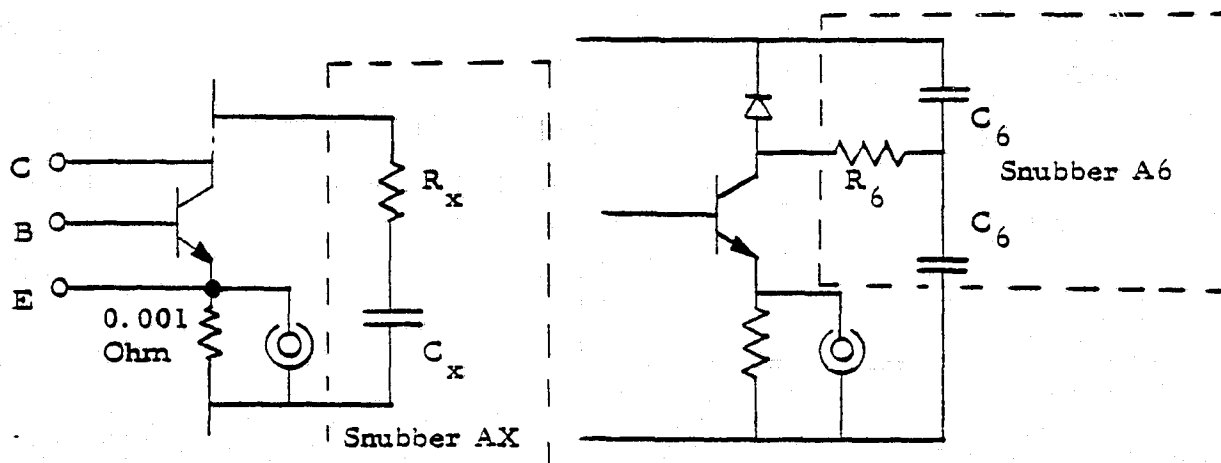


Figure 3. Snubber Configuration AX

<u>Configuration Identification</u>	<u>C_x Microfarads</u>	<u>R_x Ohms</u>
A1	0.1	5
A2	0.2	5
A3	0.5	5
A4	0.125	5
A5	0.25	5
A6	0.125	10



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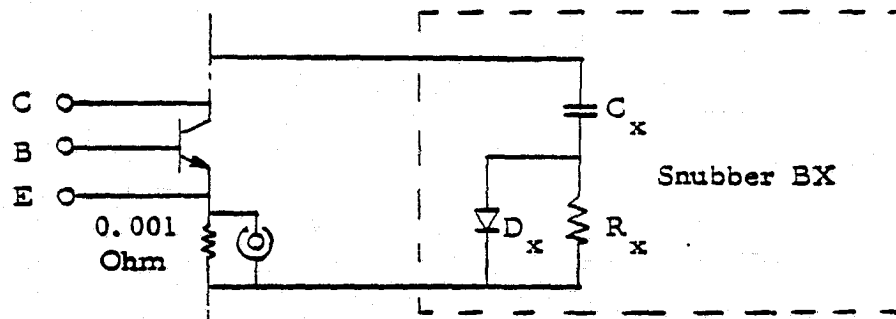


Figure 4. Snubber Configuration BX

<u>Configuration Identification</u>	<u>C_x Microfarads</u>	<u>R_x Ohms</u>	<u>D_x</u>
B1	0.2	5	SR2385
B2	0.5	5	SR2385

Note:

DX SR2385 Motorola (Special Fast Recovery, Less than 500 ns)



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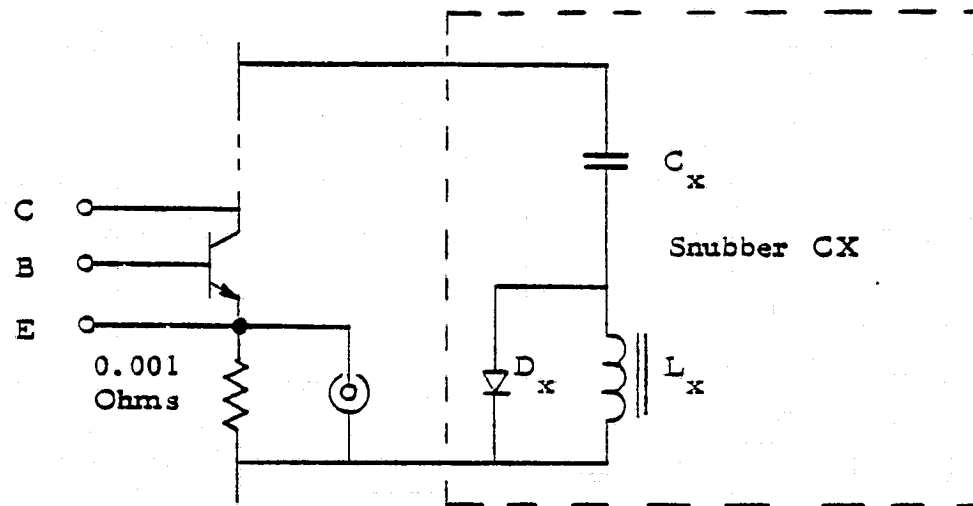


Figure 5. Snubber Configuration CX

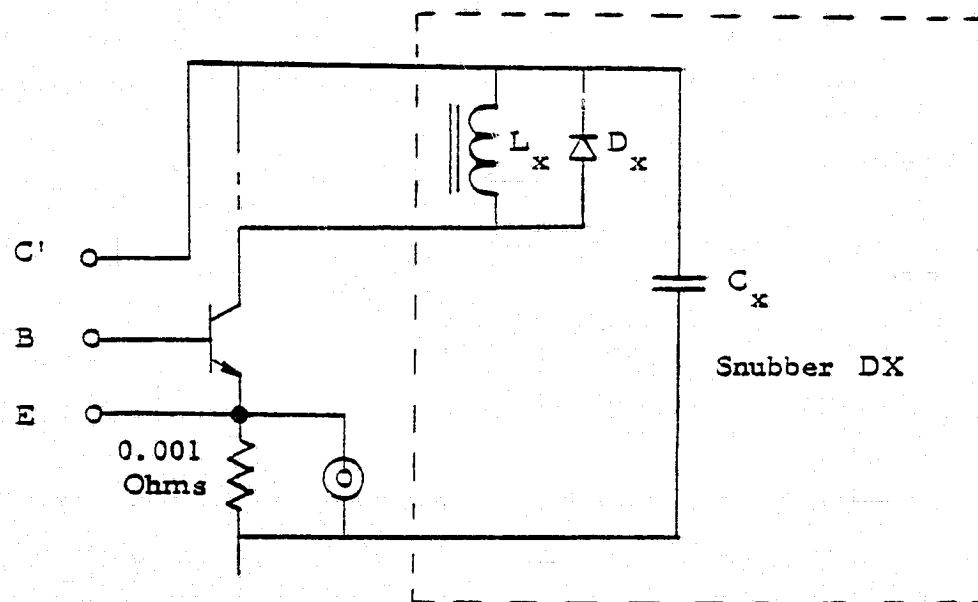


Figure 6. Snubber Configuration DX



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The tests which were conducted made use of the following instrumentation:

- o Scope: Tektronix Model 7704A with plug-ins
 - 2 ea Model 7A18
 - 1 Model 7B71
 - 1 Model 7B70
- o Multiplying Scope: Philips Model PM 3265
- o Curve Tracer: Tektronix Model 576 with high current adapter Model 176
- o Current Viewing Resistor: T&M Model W-4-001 (0.001 Ohm)
- o DC to 50 MHz Current Probe:
Tektronix Model P6042

During the tests the supply voltage and load resistance were changed, several frequencies and duty cycles were used, and the transistors were operated at several case temperatures. The base drive circuit which was used in these tests is shown in Figure 7. This circuit provides excellent base drive characteristics. The turn-on base-emitter voltage and current are well-controlled, as are the turn-off base-emitter conditions. Typical waveforms for turn-on are shown in Figure 8. Shortly after turn-on the base-emitter voltage reaches 8 V. The base current reaches a peak value of approximately 17 A in 2 microseconds, and eventually settles at 9 A. As indicated in the lower portion of Figure 8, the transistor is quickly turned on with this drive system.

Turn-off is also accomplished effectively by the base drive circuit. Typical waveforms during turn-off are shown in Figure 9. Within 1 microsecond after turn-off is initiated, the reverse base current reaches 5.5A. The reverse base-emitter voltage eventually builds to 10 V as the transistor rapidly turns off. After turn-off, the reverse base-emitter voltage stabilizes at 9 V. Both the turn-on and the turn-off drive conditions can be adjusted, as indicated in Figure 7.

The base driver circuit also has provisions for an antisaturation clamp. Figure 10 is a simplified schematic of the circuit used. The antisaturation clamp prevents the power transistor from being fully saturated during on

NOTES:

C1 - 560pF CERAMIC
 C2 - 0.1uF POLYCARB
 C3 - 10uF POLYCARB
 C4 - 20uF/20V TANTALUM
 R1 - 20uL 25W 1% NH-25 TIME
 CRX - 6 EACH 1N5615

U1 4049B IC CMOS
 U2 4049B IC CMOS
 U3 4538B IC CMOS
 Q1 2N5584
 (SELECTED FOR HIGH β)

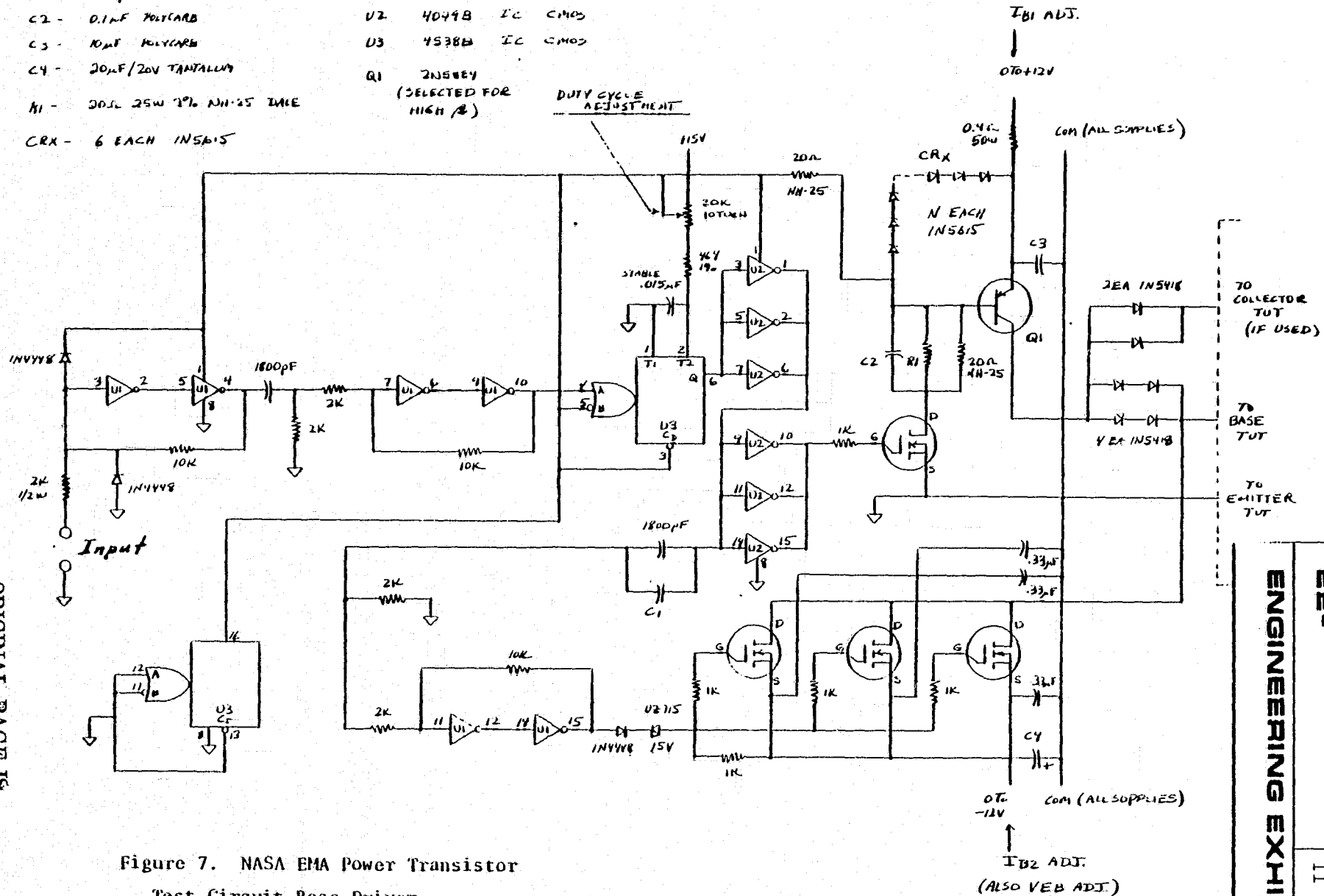


Figure 7. NASA EMA Power Transistor
 Test Circuit Base Driver

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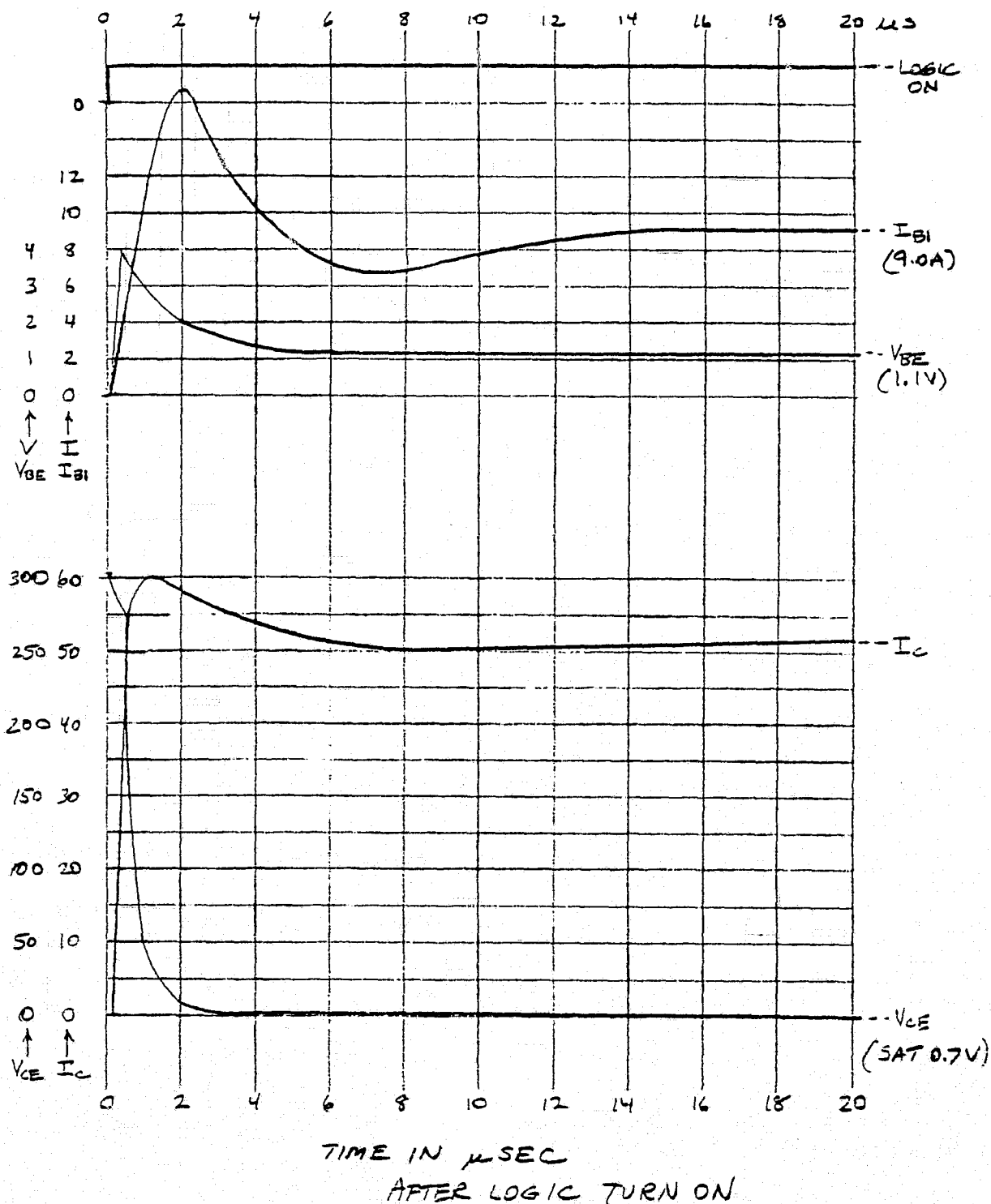


Figure 8. Turn On Waveforms

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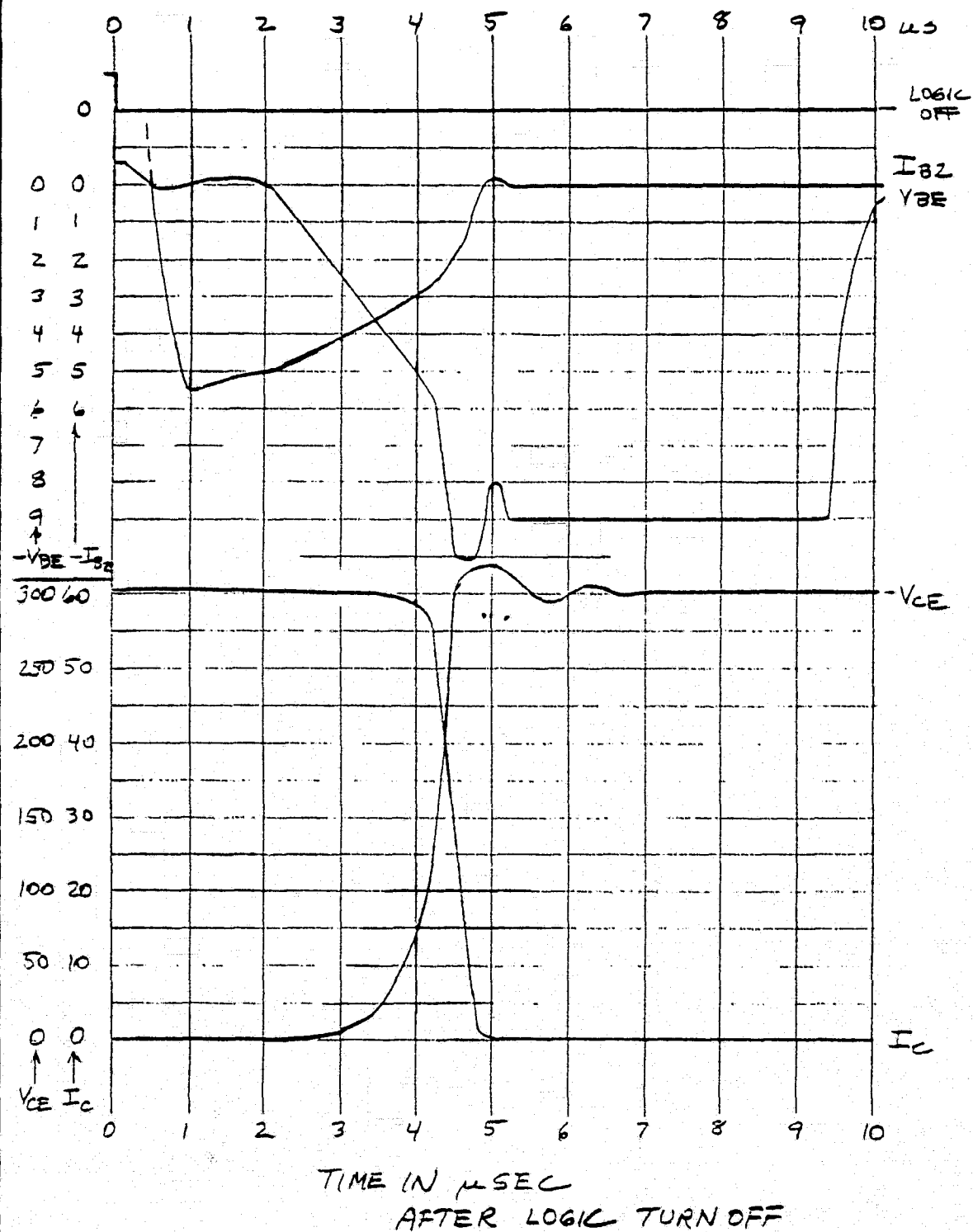


Figure 9. Turn Off Waveforms

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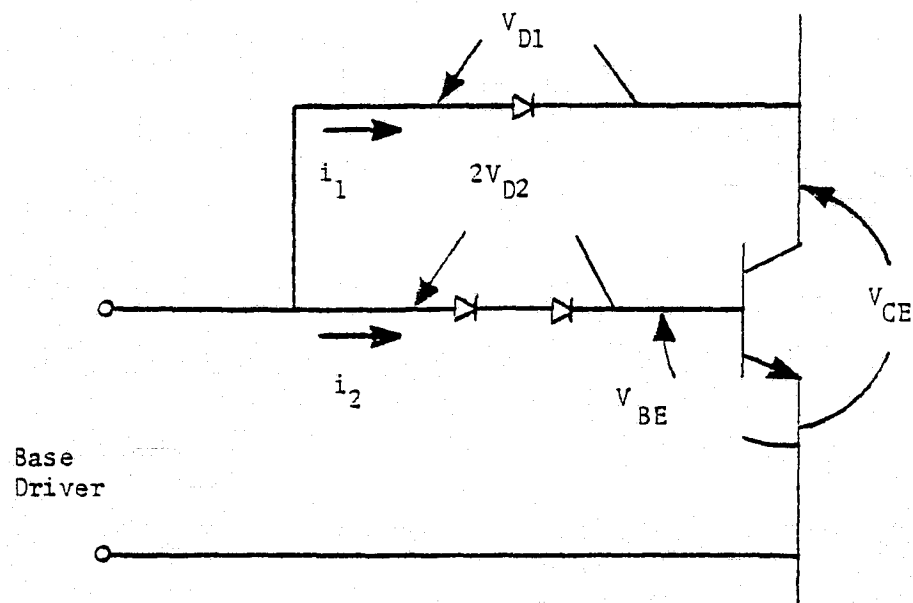


Figure 10. Power Transistor with Antisaturation Clamp

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conditions by forcing excess base drive current to flow through the collector of the transistor which is being driven. In Figure 10, if the base drive current is large,

$$V_{CE} = V_{BE} + 2 V_{D2} = V_{D1}$$

With typical operating conditions, the base-emitter voltage and the diode drops are on the order of 1 Volt each. The typical collector-emitter voltage is therefore

$$V_{CE} = 1.0 + 2(1.0) - 1.0 = 2.0 \text{ V}$$

If the load current is 60A and the base current overdrive is 10 A, the collector-emitter power dissipation during the interval when the power transistor is on would be $P_D = (60 + 10)(2.0) = 140 \text{ W}$

The antisaturation clamp reduces the switching losses and reduces the storage time of the transistor which is being driven. If transistors must be paralleled, the antisaturation clamp is highly desirable. However, with fast power transistors which do not require paralleling, the slightly reduced switching losses and improvements in storage times do not compensate for the added steady-state losses during the transistor's on state. For this reason, unless otherwise noted, the transistor tests were conducted without the use of the antisaturation clamp.

TEST RESULTS

A large number of tests were conducted during this evaluation. Test results are presented in the following discussion for high power conditions, although a large number of tests were also made at lower voltage and current levels. The Delco transistors which were tested would require paralleling in order to handle the required EMA currents. Therefore, even though test data were taken on the Delco DTS-4075 devices, they were not considered to be as suitable as the other three types of transistors. The collector-emitter and base-emitter characteristics of the test transistors (as obtained on a transistor curve-tracer) are given in Appendix A. The devices shown are:

- o Power Tech type PT4503, unit no. 2
- o RCA type J15490, unit no. 37
- o Westinghouse developmental device, unit no. 17B-6

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SBO 1078 Rev 574



Delco Electronics

General Motors Corporation
Santa Barbara Operations
8757 Hollister Avenue
Goleta, California 93017

EE- 22T-EMA-022

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16	

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Test conditions for the transistor tests are summarized in Table 2. The photo identification number is referenced for each run, the switching condition (turn-on or turn-off) is noted, the collector-emitter voltage and the collector current are tabulated, the time scale used in the display is listed, the transistor case temperature is recorded (RT indicated approximately room temperature condition), the manufacturer's code is indicated (We for Westinghouse and PT for Power Tech). Where instantaneous power readings were taken, the maximum dissipation recorded during the run is also given in Table 2.

The data sheets presented in Appendix B are largely self-explanatory. Unless otherwise noted, the device was operating near room temperature. The notation is conventional, with P_D indicating the collector dissipation (Watts). I_{B1} indicates the base current during turn-on, and I_{B2} is the turn-off base current.

TEST DATA SUMMARY

For convenience, some of the more important data obtained during the tests are summarized in Appendix C. The data summary sheets identify the device and test conditions and record both turn-on and turn-off results. Table 3 abstracts some of the more important data from Appendix C.

The first four lines in Table 3 summarize data taken at an operating frequency of 4 kHz. The last 2 lines show data taken at 8 kHz. In general, all three of the transistors tested have excellent characteristics. The RCA device had superb turn-off characteristics and low average losses. However, it did not have as much current-handling capability as either the Power Tech or Westinghouse transistors. Both Power Tech and Westinghouse devices provided adequate current and voltage margins, but the Westinghouse unit had somewhat lower losses than the Power Tech unit. Although either type could have been used for the single-channel power electronics breadboard, the Westinghouse D60T power transistor was selected, since it is an improved version of the Westinghouse 17B-6, tailored to applications such as the EMA power converter. Data sheets for the Westinghouse D60T and D62T power transistors are provided in Appendix D, as are data sheets for other power transistors.

Table 2. Test Conditions

EE-22T-EMA-022

Page	Photo Ident	Condition		V_{CE} (Volts)	I_C (AMPS)	Time Scale (μ S)	T Case (°C)	Mfgr Code	P_D Peak Watts	Freq kHz
		Turn On	Turn Off							
B1	3-2-M		x	250	50	1	RT	F	6700	4
B2	-N	x							8200	
B3	-O	x				0.2			8200	
B4	-P	x	x			5			-	
B5	-Q1		x	275	56	1	30		8200	
B6	-Q2		x				75		8200	
B7	-Q3	x					RT		9800	
B8	-Q4	x				0.2			9800	
B9	-Q5	x	x			5			-	
B10	-R1		x	300	62	1	42		10,000	
B11	-R2		x				85		10,000	
B12	-R3		x				35		-	
B13	-R4	x					RT		11,200	
B14	-R5	x				0.2			11,200	
B15	-R6	x				1			-	
B16	-R7	x				5			-	
B17	3-2-R8	x	x	300	62	5	RT	PT	-	4
B18	3-2-R9	x	x	300	62	5	RT		-	
B19	3-2-T1		x	300	59	1	35		9700	8
B20	-T2	x		300	59	1	RT		12,600	
B21	-T3	x	x	300	59	5	RT		-	
B22	3-4-B1		x	225	45	1	RT	RCA	5200	4
B23	-B2					0.2			5200	
B24	-B3	x				1			5600	
B25	-B4					0.2			5600	
B26	-B5	x	x			5			-	

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EE-22T-EMA-022

Page	Photo Ident	Turn On	Turn Off	V _{CE} (Volts)	I _C (AMPS)	Time Scale (μ S)	T Case (°C)	Mfgr Code	P _D Peak Watts	Freq kHz
B27	3-4-C1		x	250	50	1	RT	RCA	6400	4
B28	-C2		x			.2			6400	
B29	-C3		x			1	35		-	
B30	-C4	x	x			5	RT		-	
B31	-C5	x				1			6800	
B32	-C6	x				.2			6800	
B33	-C7	x				1			-	
B34	-C8	x				20			-	
B35	-C9	x				20			-	
B36	-C10	x	x			5			-	
B37	2-25-A	x		250	52	1.0	35	We	7100	12
B38	2-25-B		x				85		7400	
B39	2-25-C	x				0.2	35		10,400	
B40	2-25-D	x					85		10,700	
B41	2-25-E	x	x			10	35			
B42	2-25-F	x	x				85			
B43	2-25-6		x	250	60	1.0	35		9400	
B44	2-25-H	x			52				13,600	
B45	2-25-I	x				0.2				
B46	2-17-F		x	275	60	1	RT	We	9400	4
B47	2-17-G	x								
B48	-H	x							10,400	
B49	-I					0.2				
B50	-J					5				
B51	-K	x	x			5				

EE-22T-EMA-022

Page	Photo Ident	Turn On	Turn Off	V CE (Volts)	I C (AMPS)	Time Scale (μ S)	T Case ($^{\circ}$ C)	Mfgr Code	P _D Peak Watts	Freq kHz
B52	2-17-L		x	300	60	1	RT	We	9700	4
B53	-M									
B54	-N									
B55	-O									
B56	-P	x							11,600	
B57	-Q					0.2			11,600	
B58	-R					2				
B59	-S					5				
B60	-T					2				
B61	-U	x	x			5				
B62	2-24-T		x	300	60	1	35		9800	8
B63	-U		x				85		9200	
B64	-V						RT			
B65	-VA						RT			
B66	-W	x							12,000	
B67	-WA					0.2			12,000	
B68	2-24-X	x		300	60	1	RT	We		8
B69	-Y	x	x			5				
B70	-Z	x	x			5				

Table 3. Data Summary

EE-22T-EMA-022

Ref Page	Mfgr	V _{CE} Volts	I _C Amps	Case Temp o C	Turn-off Data		T _S μ S	T _F μ S	Turn-on Data				Freq kHz
					P _D Avg W	P _D Peak W			P _D Avg W	P _D Peak W	T _D μ S	T _R μ S	
C1	PT	300	62	<50	52	10,000	3.5	1.6	38	11,000	0.1	0.5	4
C3	We	300	60	<50	30	9800	3.6	0.7	36	11,500	0.1	0.4	4
C5	RCA	250	50	<35	11	6100	1.8	0.6	15	6600	0.2	0.5	4
C7	We	250	55	<35	18	7400	4.2	0.6	23	9200	0.08	0.4	4
C9	We	300	60	35	76	12,000	4.2	0.7	86	12,000	0.1	0.4	8
C11	PT	300	59	35	147	10,500	3.8	3.0	126	12,600	0.2	0.8	8

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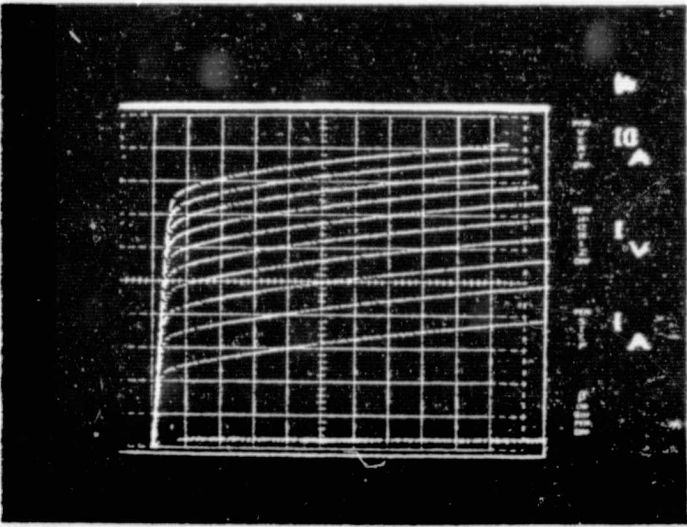
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APPENDIX A

CURVE TRACER DATA

This appendix presents data taken on the candidate power transistors using a Tektronix Model 576 Curve Tracer with a Model 176 High Current Adapter.

DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE JOB NO. EE-22T-EMA-022	PAGE A1
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED CHECKED APPROVED	
D.U.T. TYPE <u>PowerTech PT4503</u> , UNIT NO. <u>2</u> CIRCUIT <u>Tek 576 w/176 Curve Tracer</u> OTHER _____ $I_{B1} =$ _____ AMPS, $-I_{B2} =$ _____ AMPS $V_{CE} =$ _____ V PEAK, $I_C =$ _____ A PEAK OTHER _____ FREQUENCY _____ KHZ, DUTY CYCLE ON _____ % SNUBBER _____			
		Vert: I_c 10A/div Horiz: V_{ce} 1V/div Base drive: 1A/step 10 steps	
PIX NO. _____, ADDITIONAL COMMENTS _____			

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE A2
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED CHECKED APPROVED		

D.U.T. TYPE PowerTech PT4503, UNIT NO. 2

CIRCUIT Tek 576 w/176 Curve Tracer

OTHER _____

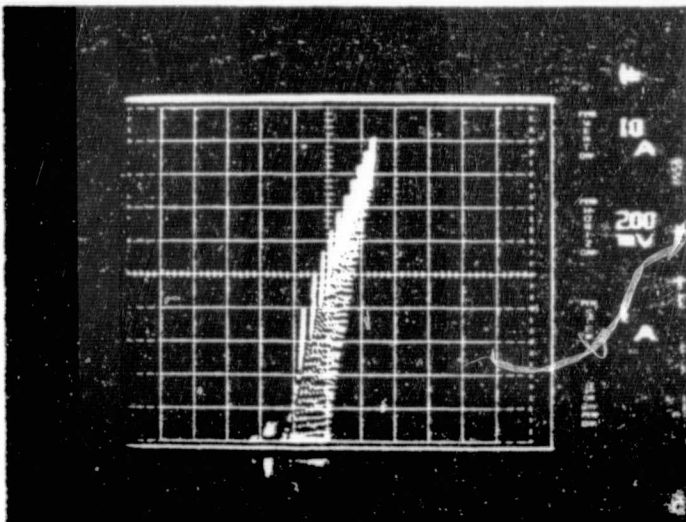
I_{B1} = _____ AMPS, $-I_{B2}$ = _____ AMPS

V_{CE} = _____ V PEAK, I_C = _____ A PEAK

OTHER _____

FREQUENCY _____ KHZ, DUTY CYCLE ON _____ %

SNUBBER _____



Vert: I_C
 10 A/div

Horiz: V_{BE}
 0.2 V/div

Base drive:
 1 A/step
 10 steps

PIX NO. _____, ADDITIONAL COMMENTS V_{BE} not

Kelvin sensed, indicated 100 mV higher than actual at 10 A.

DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE JOB NO. EE-22T-EMA-022	PAGE A3
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.B. Barrett</i> 3/2/77 CHECKED	DATE
		APPROVED	

D.U.T. TYPE RCA J-15490, UNIT NO. 37

CIRCUIT TeK 576 w/176 Curve Tracer

OTHER _____

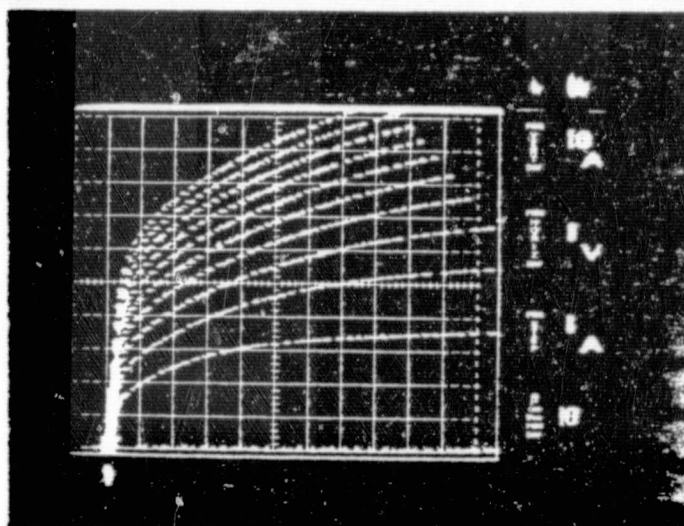
I_{S1} = _____ AMPS, $-I_{B2}$ = _____ AMPS

V_{CE} = _____ V PEAK, I_C = _____ A PEAK

OTHER _____

FREQUENCY _____ KHZ, DUTY CYCLE ON _____ %

SNUBBER _____



Vert I_C @ 10A/DIV

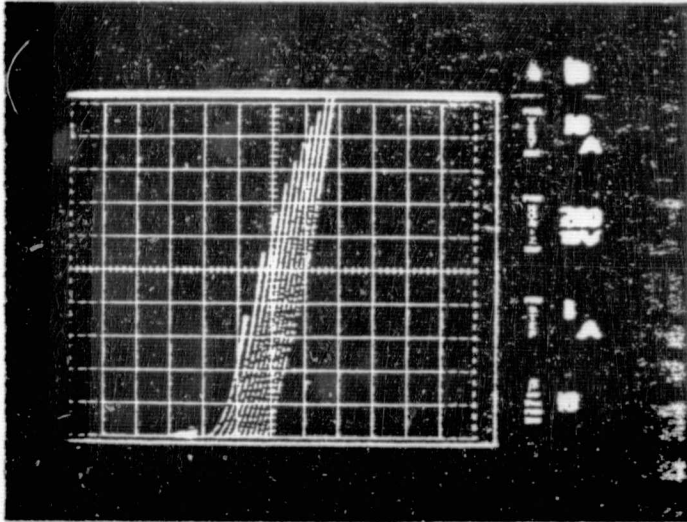
Horiz V_{CE} @ 1V/DIV

Base drive
1A/step
10 steps

PIX NO. 3-2-CT1, ADDITIONAL COMMENTS _____

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE A4
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barnett</i> 3/2/77 CHECKED APPROVED		
D.U.T. TYPE <u>RCA J-15490</u> , UNIT NO. <u>37</u> CIRCUIT <u>Tek 576 w/176 Curve Tracer</u> OTHER _____ $I_{B1} =$ _____ AMPS, $-I_{B2} =$ _____ AMPS $V_{CE} =$ _____ V PEAK, $I_C =$ _____ A PEAK OTHER _____ FREQUENCY _____ KHZ, DUTY CYCLE ON _____ % SNUBBER _____				
 <i>Vert I_c @ 10A/DIV</i> <i>Hory V_{BE} @ 200mV/DIV</i> <i>Base drive</i> <i>1A/step</i> <i>10 steps</i>				
PIX NO. <u>3-2-CT2</u> , ADDITIONAL COMMENTS _____ <u>Note:</u> V_{BE} is not Kelvin sensed - at 10A (I_B) it indicates ≈ 125 mV higher than true value				

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barnett</i>	DATE 2-14-77	
		CHECKED		
		APPROVED		

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT CURVE TRACER

OTHER $I_C / V_{CE} / I_B$ 10 Steps

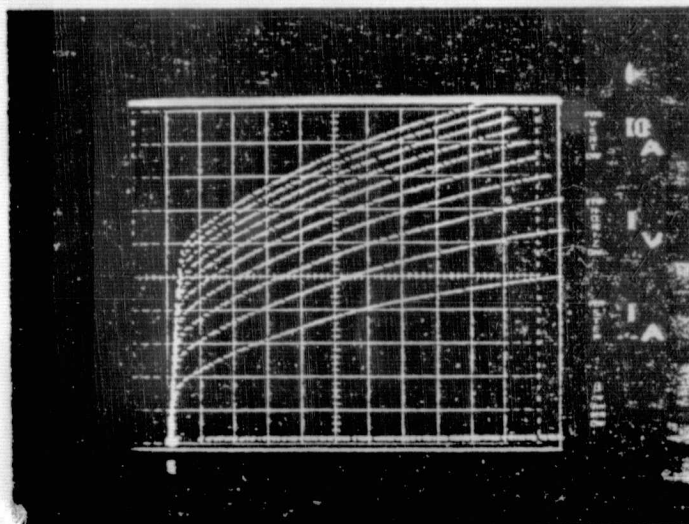
I_{B1} = _____ AMPS, $-I_{B2}$ = _____ AMPS

V_{CE} = _____ V PEAK, I_C = _____ A PEAK

OTHER _____

FREQUENCY _____ KHZ, DUTY CYCLE ON _____ %

SNUBBER _____



PIX NO. 2-14-C, ADDITIONAL COMMENTS _____

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TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

PREPARED

DATE

CHECKED

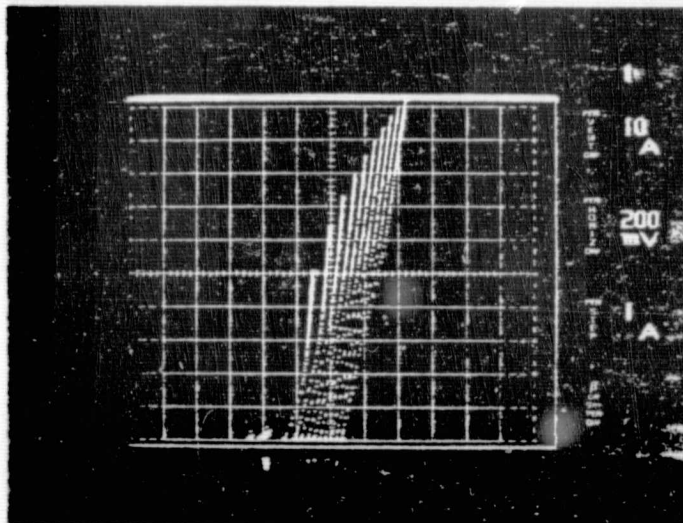
APPROVED

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6CIRCUIT CURVE TRACEROTHER $I_C / V_{BE} / I_B$ 10 steps I_{B1} = _____ AMPS, $-I_{B2}$ = _____ AMPS V_{CE} = _____ V PEAK, I_C = _____ A PEAK

OTHER _____

FREQUENCY _____ KHZ, DUTY CYCLE ON _____ %

SNUBBER _____



Note:

$V_{BE} \approx 125 \text{ mV}$
high at
 $I_B = 10 \text{ A}$
(no Kelvin sense
on V_{BE})

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APPENDIX B

WAVEFORM PHOTOGRAPHS

This appendix presents waveform photographs of the candidate power transistors taken under various turn-on and turn-off conditions.

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED CHECKED APPROVED	DATE 3/2/77	

D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

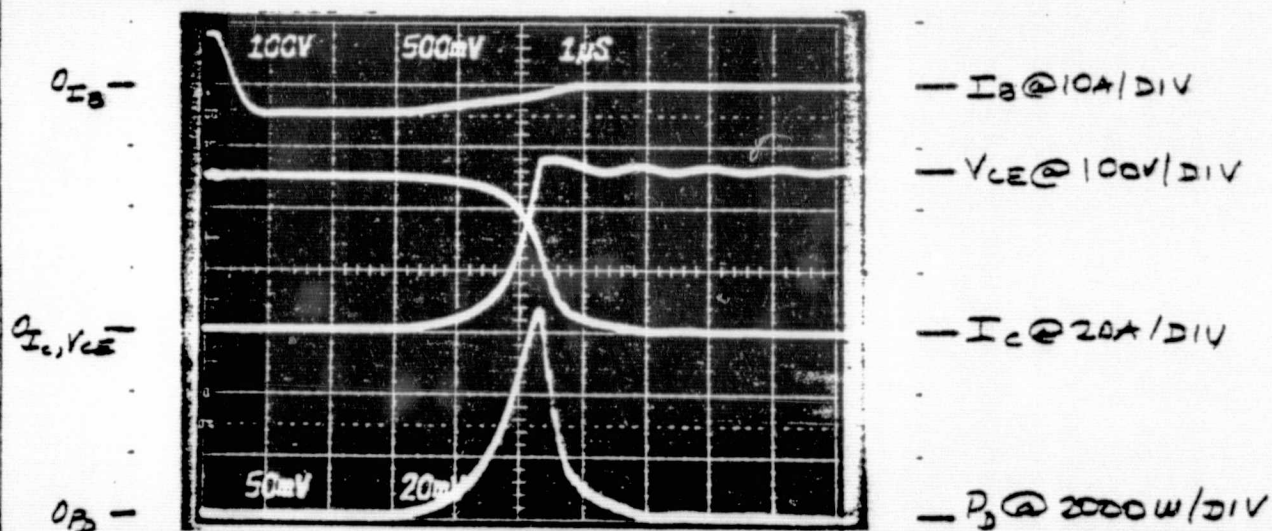
$I_{B1} = (16Apk)$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. AG



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			EE-22T-EMA-022	82
TITLE NASA EM-ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C.H. Barrett</i>	DATE 3/2/77	
		CHECKED		
		APPROVED		

D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

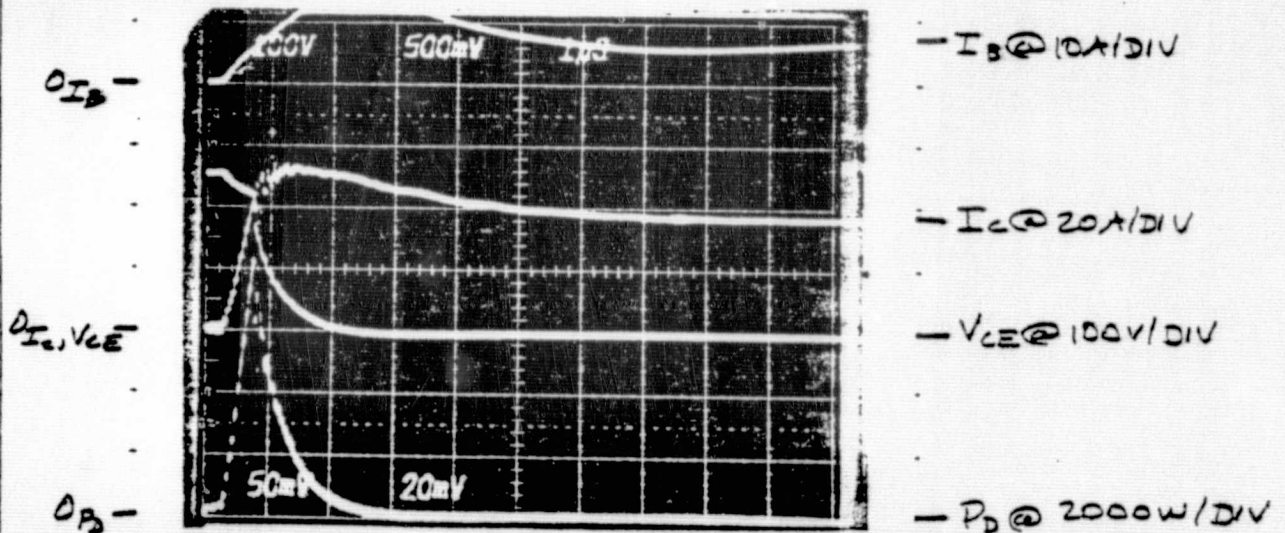
$I_{B1} = (16A_{pk})$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6



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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS	PREPARED <i>C.H. Barrett</i> CHECKED DATE 3/2/77		
		APPROVED	

D.U.T. TYPE POWERTECH PT-45D3, UNIT NO. 2

CIRCUIT _____

OTHER _____

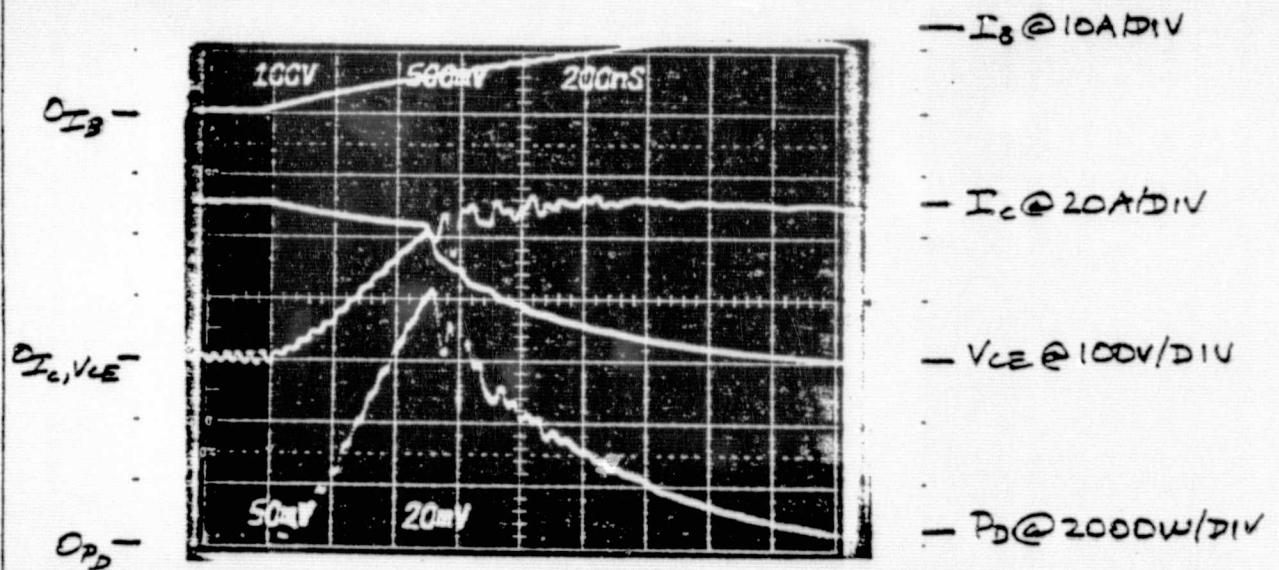
$I_{B1} = (16A_{pk})$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6



PIX NO. 3-2-0, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barrett</i> 3/2/77 CHECKED APPROVED		

D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

$I_{B1} = \underline{(16Apk)} \underline{8}$ AMPS, $-I_{B2} = \underline{(-8V)} \underline{5}$ AMPS

$V_{CE} = \underline{250}$ V PEAK, $I_C = \underline{50}$ A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. AG

O_{I_B} -

$O_{I_C, V_{CE}}$ -

O_{P_B} -

- $I_B @ 10A/DIV$

- $I_C @ 20A/DIV$

- $V_{CE} @ 100V/DIV$

- $P_B @ 2000W/DIV$

PIX NO. 3-2-P, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS			PREPARED <i>C.H. Barrett</i> CHECKED DATE 3/2/77 APPROVED	

D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

$I_{B1} = \underline{(16A pk)} \quad 8 \text{ AMPS}, \quad -I_{B2} = \underline{(-8V)} \quad 5 \text{ AMPS}$

$V_{CE} = \underline{275} \text{ V PEAK}, \quad I_C = \underline{56} \text{ A PEAK}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6

$O_{I_B} -$

$O_{I_C, V_{CE}} -$

$O_{P_D} -$

$- I_B @ 10A/DIV$

$- V_{CE} @ 100V/DIV$

$- I_C @ 20A/DIV$

$- P_D @ 2000W/DIV$

PIX NO. 3-2-Q1, ADDITIONAL COMMENTS Tease 30°C

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE B6
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C.H. Barrett</i> CHECKED DATE 3/2/77		
D.U.T. TYPE <u>POWERTECH PT-45D3</u> UNIT NO. <u>2</u>				
CIRCUIT _____				
OTHER _____				
$I_{B1} = $ <u>(16A pk)</u> <u>8</u> AMPS, $-I_{B2} = $ <u>(-8V)</u> <u>5</u> AMPS				
$V_{CE} = $ <u>275V</u> PEAK, $I_C = $ <u>56</u> A PEAK				
OTHER _____				
FREQUENCY <u>4</u> KHZ, DUTY CYCLE ON <u>85</u> %				
SNUBBER <u>CONF. A6</u>				
I_B I_C, V_{CE} P_D $-I_B @ 10A/DIV$ $-V_{CE} @ 100V/DIV$ $-I_C @ 20A/DIV$ $-P_D @ 2000W/DIV$				
PIX NO. <u>3-2-Q2</u> , ADDITIONAL COMMENTS <u>Trace 75°C</u> <u>stabilized</u>				
NOTE: INCREASED STORAGE AND FALL TIMES				

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	PREPARED <u>Ch. Bant</u> 3/2/77 CHECKED APPROVED		DATE
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS			

D.U.T. TYPE POWERTECH PT-45D3, UNIT NO. 2

CIRCUIT _____

OTHER _____

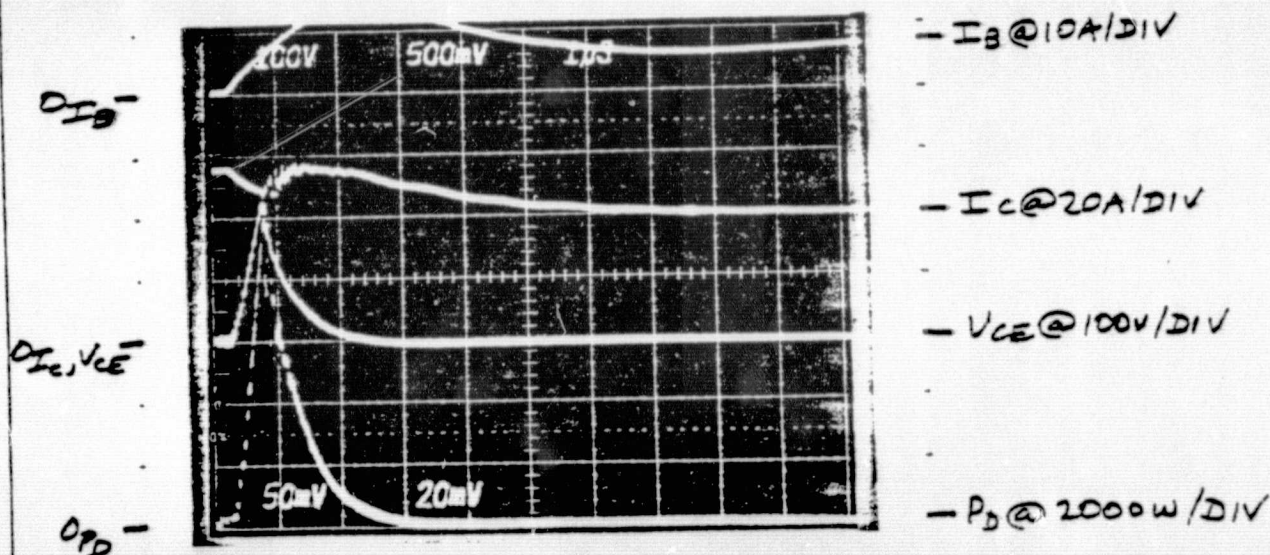
$I_{B1} = (16\mu k) \quad 8 \text{ AMPS}, \quad -I_{B2} = (-8V) \quad 5 \text{ AMPS}$

$V_{CE} = 275 \text{ V PEAK}, \quad I_C = 56 \text{ A PEAK}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6



PIX NO. 3-2-Q3, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C.H. Barrett</i> CHECKED DATE 3/2/77 APPROVED		

D.U.T. TYPE POWERTECH PT-45D3, UNIT NO. 2

CIRCUIT _____

OTHER _____

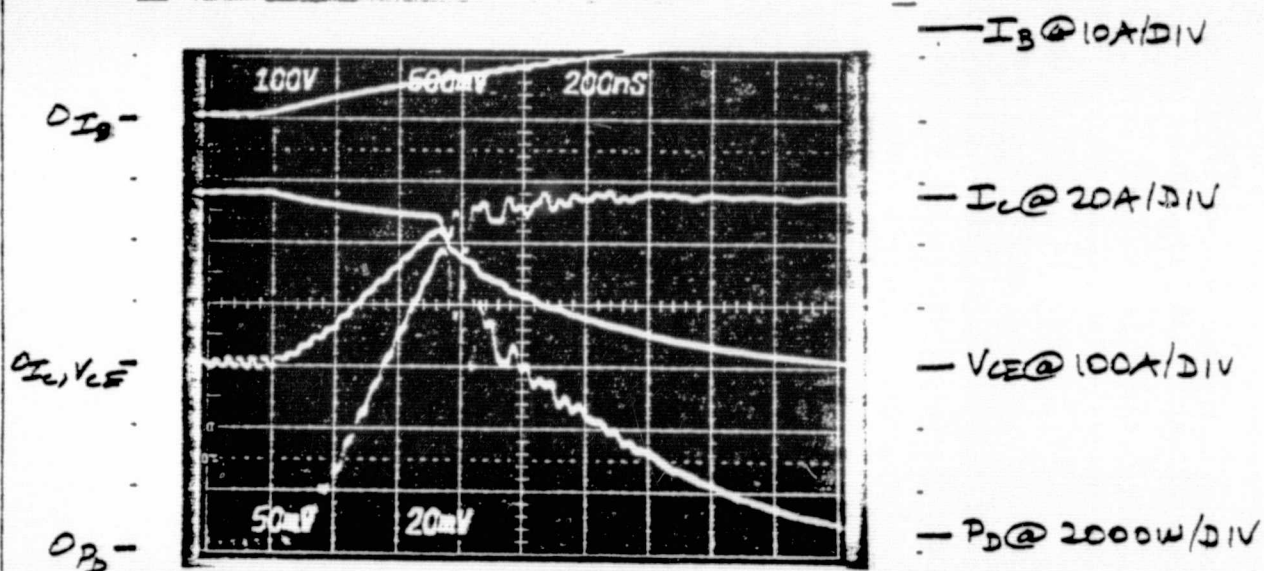
$I_{B1} = (16A_{PK})$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS

$V_{CE} =$ 275 V PEAK, $I_C =$ 56 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6



PIX NO. 3-2-Q4, ADDITIONAL COMMENTS _____

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B9

TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

PREPARED

CHECKED

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DATE

3/2/77

D.U.T. TYPE POWERTECH PT-4503

UNIT NO. 2

CIRCUIT

OTHER

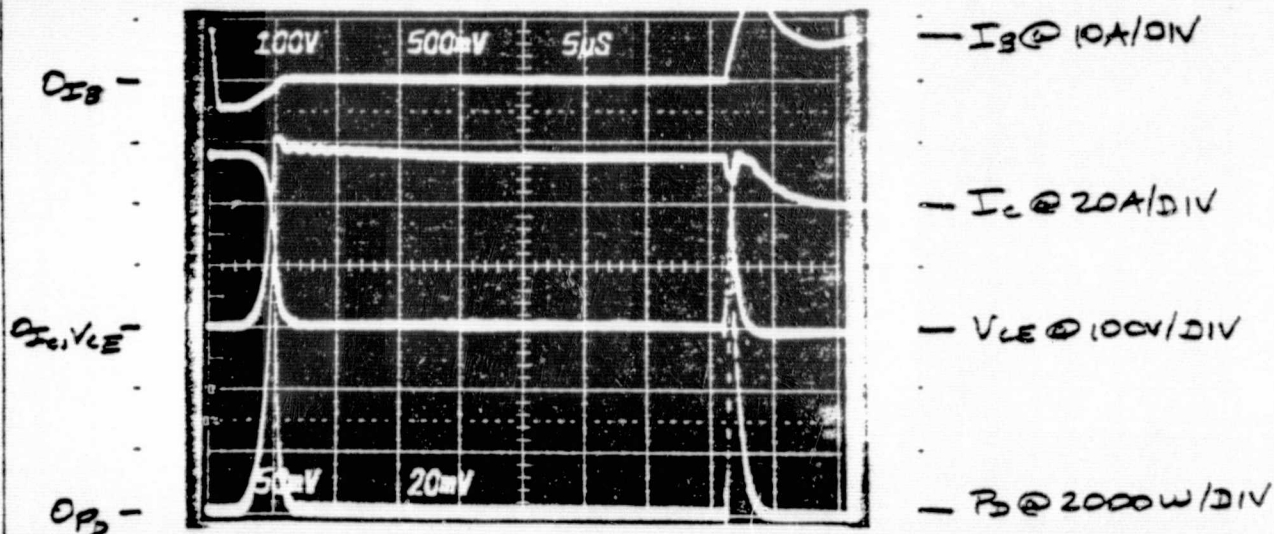
$I_{B1} = (16A_{pk})$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS

$V_{CE} =$ 275V PEAK, $I_C =$ 56A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6



PIX NO. 3-2-Q5, ADDITIONAL COMMENTS

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE B10
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C.H. Barrett</i> CHECKED DATE 3/2/77 APPROVED		

D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

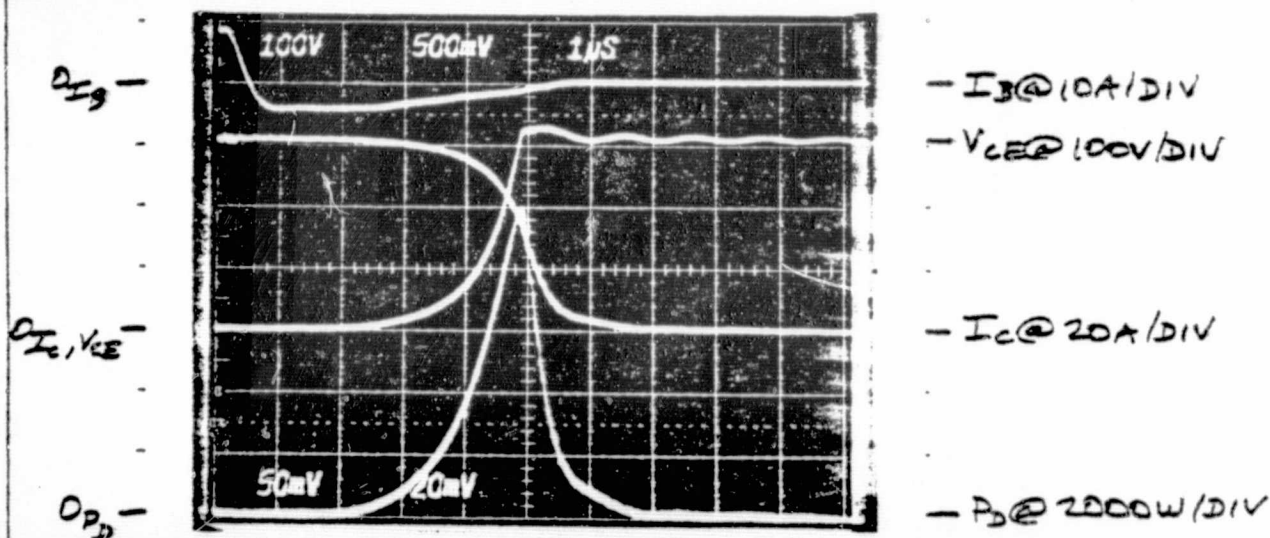
$I_{B1} = \underline{(16A pk)} \quad \underline{8} \text{ AMPS}, \quad -I_{B2} = \underline{(-8V)} \quad \underline{5} \text{ AMPS}$

$V_{CE} = \underline{300} \text{ V PEAK}, \quad I_C = \underline{62} \text{ A PEAK}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85 %

SNUBBER CONF. A6



PIX NO. 3-2-R1, ADDITIONAL COMMENTS $T_{case} = 42^\circ C$

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barrett</i> CHECKED	DATE 3/2/77
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D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

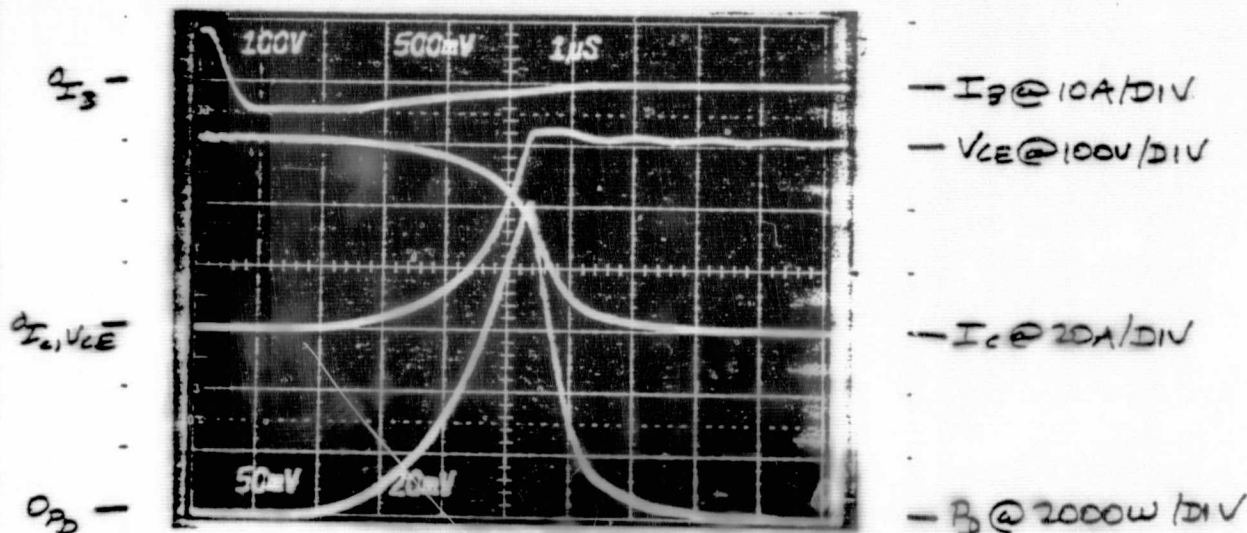
$I_{B1} = (16A_{pk})$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 62 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85 %

SNUBBER CONF. A6



PIX NO. 3-2-R2, ADDITIONAL COMMENTS $T_{case} = 85^{\circ}C$
almost stabilized

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DEVICE TESTS

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D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT

OTHER

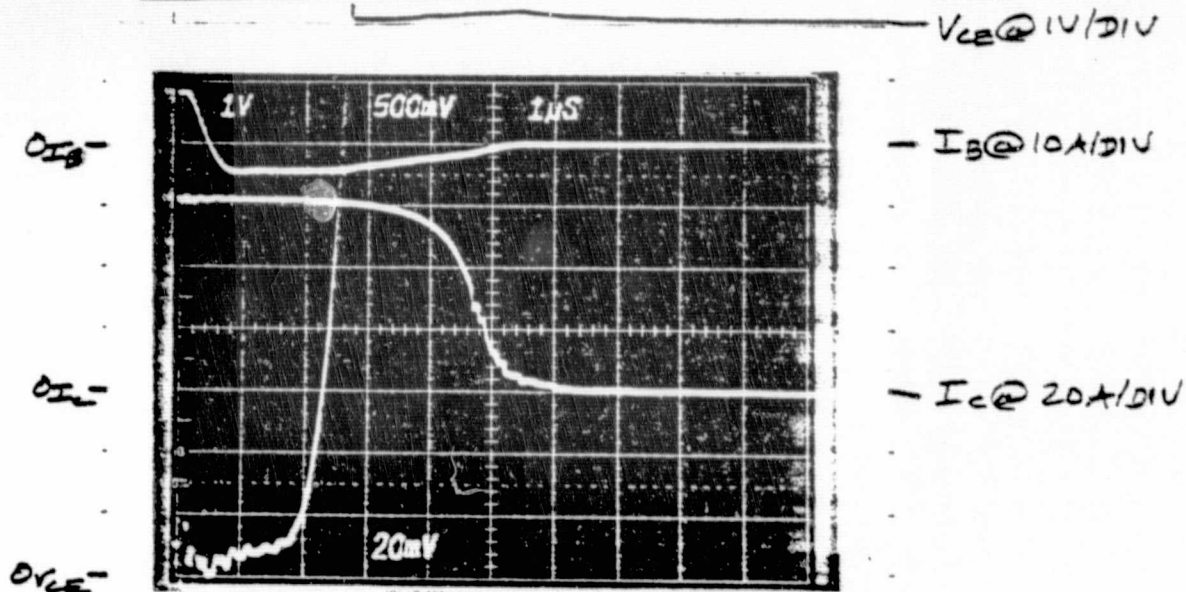
$I_{B1} = (16Apk)$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 62 A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 85

SNUBBER CONF. AG



PIX NO. 3-2-R3, ADDITIONAL COMMENTS $T_{case} = 35^{\circ}C$

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C.H. Barrett</i> CHECKED DATE 3/2/77 APPROVED		
D.U.T. TYPE <u>POWERTECH PT 45D3</u> , UNIT NO. <u>2</u> CIRCUIT _____ OTHER _____ $I_{B1} = $ <u>(16A pk)</u> <u>8</u> AMPS, $-I_{B2} = $ <u>(-8V)</u> <u>5</u> AMPS $V_{CE} = $ <u>300</u> V PEAK, $I_C = $ <u>62</u> A PEAK OTHER _____ FREQUENCY <u>4</u> KHz, DUTY CYCLE ON <u>85</u> % SNUBBER <u>CONF. A6</u>				
I_{B1} I_{B2} V_{CE} P_D $-I_{B1} @ 10A/DIV$ $-I_{B2} @ 20A/DIV$ $-V_{CE} @ 100V/DIV$ $-P_D @ 2000W/DIV$				
PIX NO. <u>3-2-R4</u> , ADDITIONAL COMMENTS _____				

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <u>A.H. Barrett</u> DATE <u>3/2/77</u> CHECKED _____ APPROVED _____		

D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

$I_{B1} = \underline{(16Apk)} \quad \underline{8} \text{ AMPS}, \quad -I_{B2} = \underline{(-8V)} \quad \underline{5} \text{ AMPS}$

$V_{CE} = \underline{300} \text{ V PEAK}, \quad I_C = \underline{62} \text{ A PEAK}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6

O_{I_B}

 $O_{I_C, V_{CE}}$

 O_{P_D}

— $I_B @ 10A/DIV$

— $I_C @ 20A/DIV$

— $V_{CE} @ 100V/DIV$

— $P_D @ 2000W/DIV$

PIX NO. 3-2-R5, ADDITIONAL COMMENTS _____

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D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

$I_{B1} = \underline{(16A_{pk})}$ 8 AMPS, $-I_{B2} = \underline{(-8V)}$ 5 AMPS

$V_{CE} = \underline{300}$ V PEAK, $I_C = \underline{62}$ A PEAK

OTHER _____

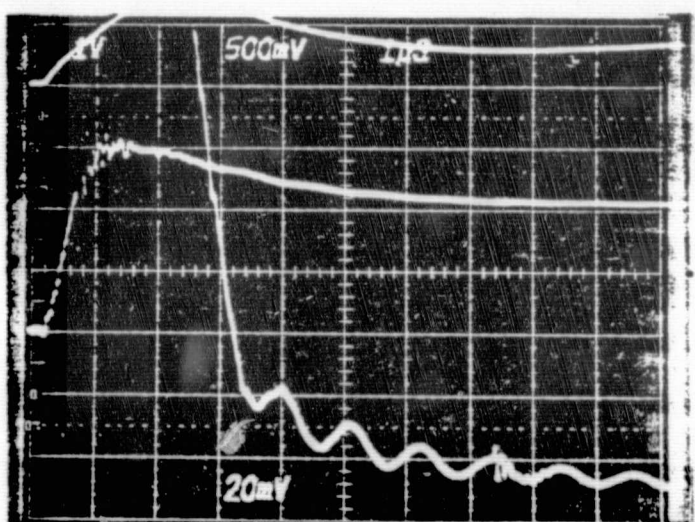
FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6

O_{I_B}

 O_{I_C}

 $O_{V_{CE}}$



$-I_B @ 10A/DIV$

 $-I_C @ 20A/DIV$

 $-V_{CE} @ 1V/DIV$

PIX NO. 3-2-R6, ADDITIONAL COMMENTS _____

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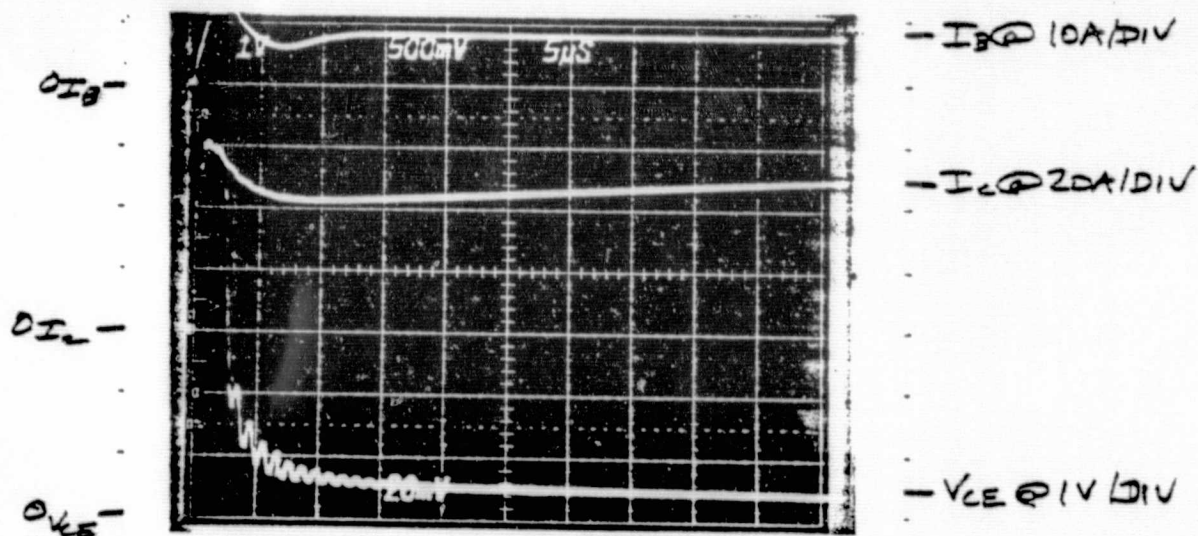
D.U.T. TYPE POWERTECH PT-4503UNIT NO. 2

CIRCUIT _____

OTHER _____

 $I_{B1} = (16A_{pk})$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS $V_{CE} =$ 300 V PEAK, $I_C =$ 62 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85 %SNUBBER CONF. A6PIX NO. 3-2-R7, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C.H. Barrett</i> CHECKED DATE 3/2/77 APPROVED		

D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

$I_{B1} =$ (16A pk) 8 AMPS, $-I_{B2} =$ (-8V) 5 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 62 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6

O_{I_B} -

$O_{I_C, V_{CE}}$ -

O_{P_D} -

$-I_B @ 10A/DIV$

$-I_C @ 20A/DIV$

$-V_{CE} @ 100V/DIV$

$-P_D @ 2000W/DIV$

PIX NO. 3-2-R8, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C.H. Barrett</i> CHECKED DATE 3/2/77 APPROVED		

D.U.T. TYPE POWERTECH PT-45D3, UNIT NO. 2

CIRCUIT _____

OTHER _____

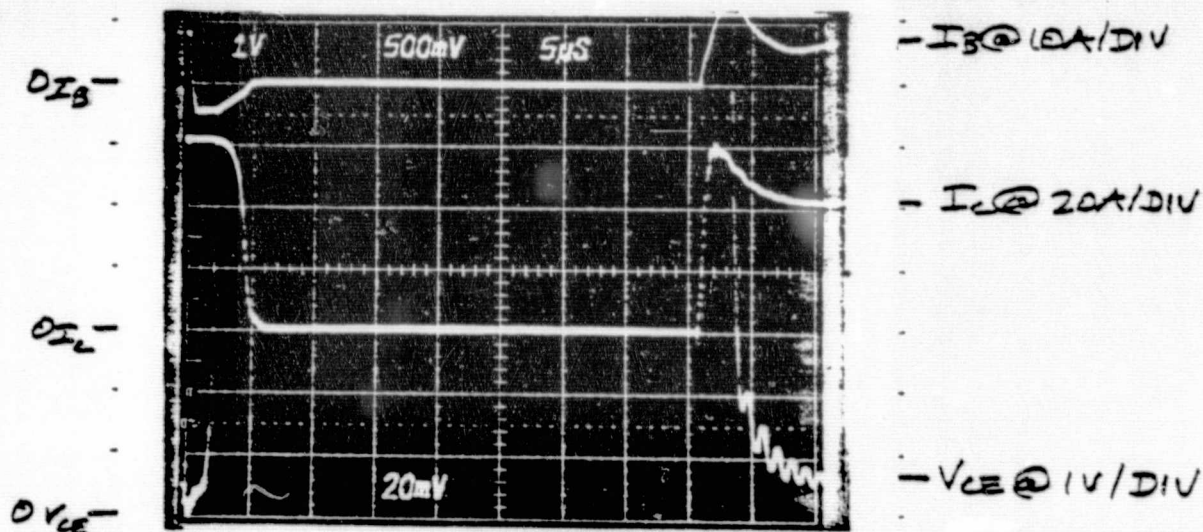
$I_{B1} = \underline{(16\mu k)} \quad \underline{8} \text{ AMPS}, \quad -I_{B2} = \underline{(-8V)} \quad \underline{5} \text{ AMPS}$

$V_{CE} = \underline{300} \text{ V PEAK}, \quad I_C = \underline{62} \text{ A PEAK}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 85%

SNUBBER CONF. A6



PIX NO. 3-2-R9, ADDITIONAL COMMENTS _____

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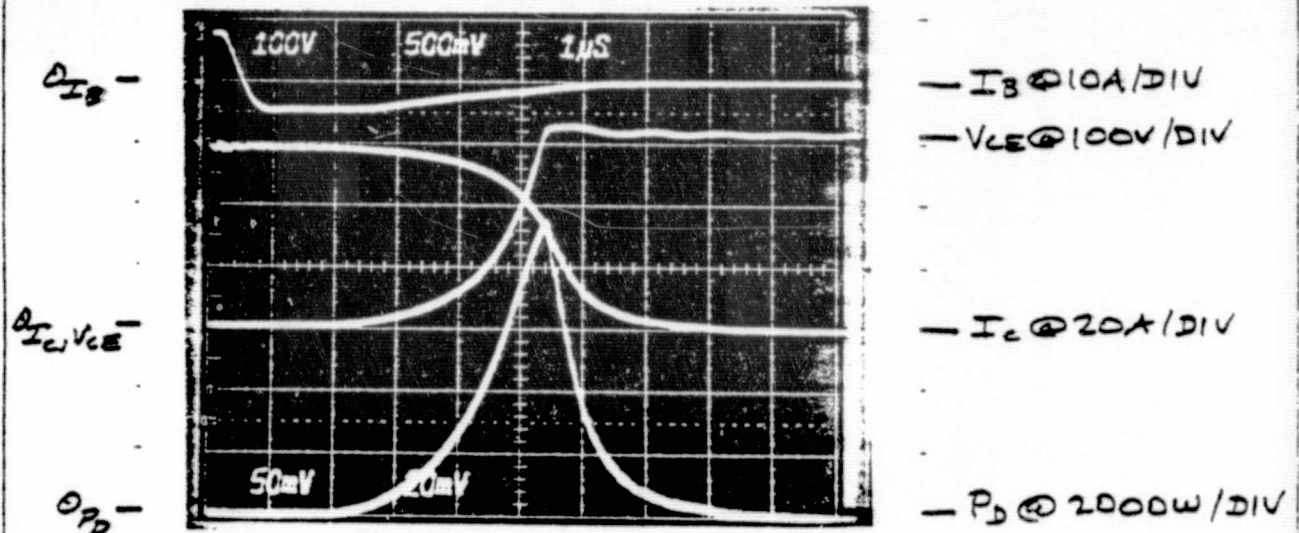
D.U.T. TYPE POWERTECH PT-45D3, UNIT NO. 2

CIRCUIT

OTHER

 $I_{B1} = (16Aph) \quad 8 \text{ AMPS,} \quad -I_{B2} = (-8V) \quad 5 \text{ AMPS}$ $V_{CE} = 300 \text{ V PEAK,} \quad I_C = 59 \text{ A PEAK}$

OTHER

FREQUENCY 8 KHZ, DUTY CYCLE ON 84 %SNUBBER CONF. A6PIX NO. 3-2-T1, ADDITIONAL COMMENTS $T_{case} = 35^\circ C$

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <u>G.H. Barrett</u> DATE <u>3/2/77</u> CHECKED _____ APPROVED _____		
D.U.T. TYPE <u>POWERTECH PT-4503</u> , UNIT NO. <u>2</u> CIRCUIT _____ OTHER _____ $I_{B1} = \underline{(16 \text{ A pk})}$ <u>8</u> AMPS, $-I_{B2} = \underline{(-8 \text{ V})}$ <u>5</u> AMPS $V_{CE} = \underline{300}$ V PEAK, $I_C = \underline{55}$ A PEAK OTHER _____ FREQUENCY <u>8</u> KHZ, DUTY CYCLE ON <u>84</u> % SNUBBER <u>CONF. AG</u>				
O_{I_B} $O_{I_C, V_{CE}}$ O_{P_D} $-I_B @ 10 \text{ A/DIV}$ $-I_C @ 20 \text{ A/DIV}$ $-V_{CE} @ 100 \text{ V/DIV}$ $-P_D @ 2000 \text{ W/DIV}$				
PIX NO. <u>3-2-T2</u> , ADDITIONAL COMMENTS _____				

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barrett</i>	DATE 3/2/77	
		CHECKED		
		APPROVED		

D.U.T. TYPE POWERTECH PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____

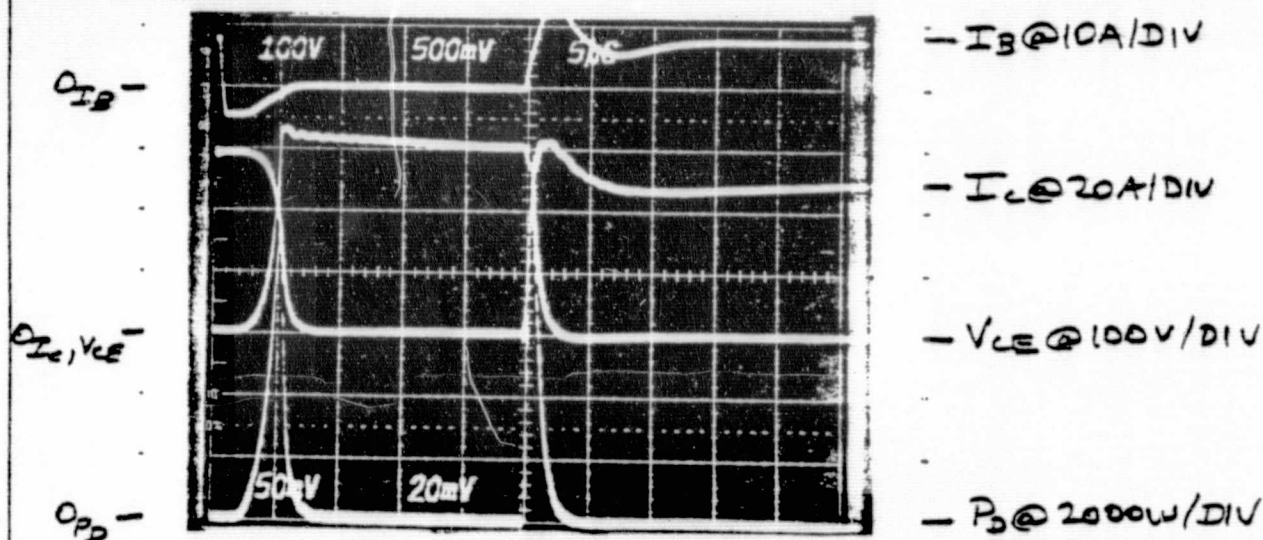
$I_{B1} = (16A_{pk})$ 8 AMPS, $-I_{B2} = (-8V)$ 5 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 59 A PEAK

OTHER _____

FREQUENCY 8 KHZ, DUTY CYCLE ON 84 %

SNUBBER CONF. A6



PIX NO. 3-2-T3, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED A.H. Barrett CHECKED DATE 3/4/77	APPROVED

D.U.T. TYPE RCA J-15490, UNIT NO. 37

CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER _____

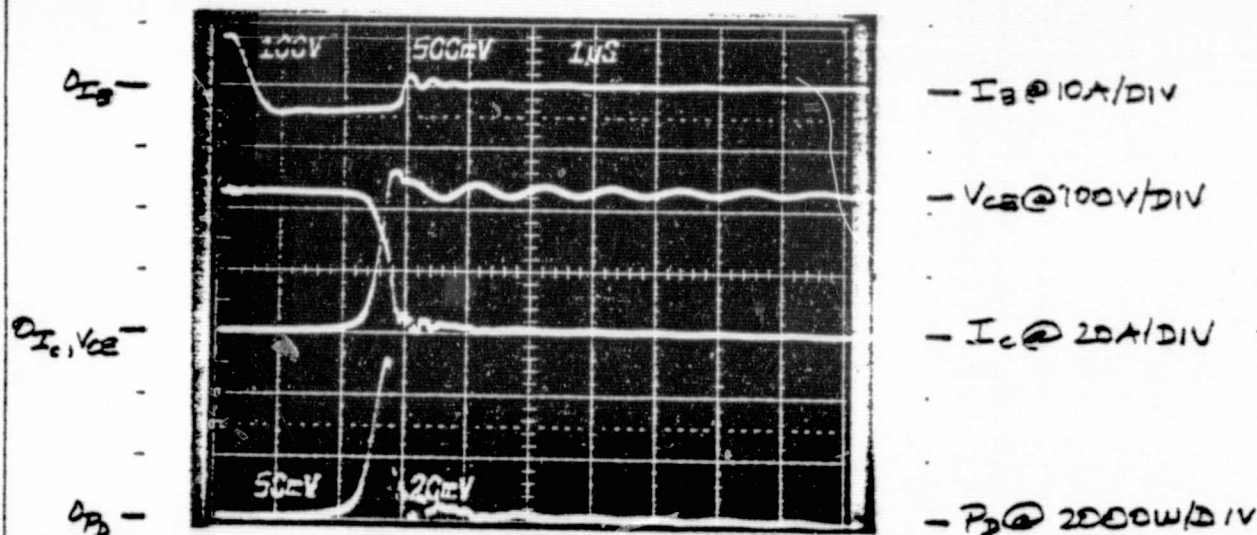
$I_{B1} = (16 \text{ Apk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS

$V_{CE} =$ 225 V PEAK, $I_C =$ 45 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80%

SNUBBER CONF. 46



PIX NO. 3-4-B1, ADDITIONAL COMMENTS _____

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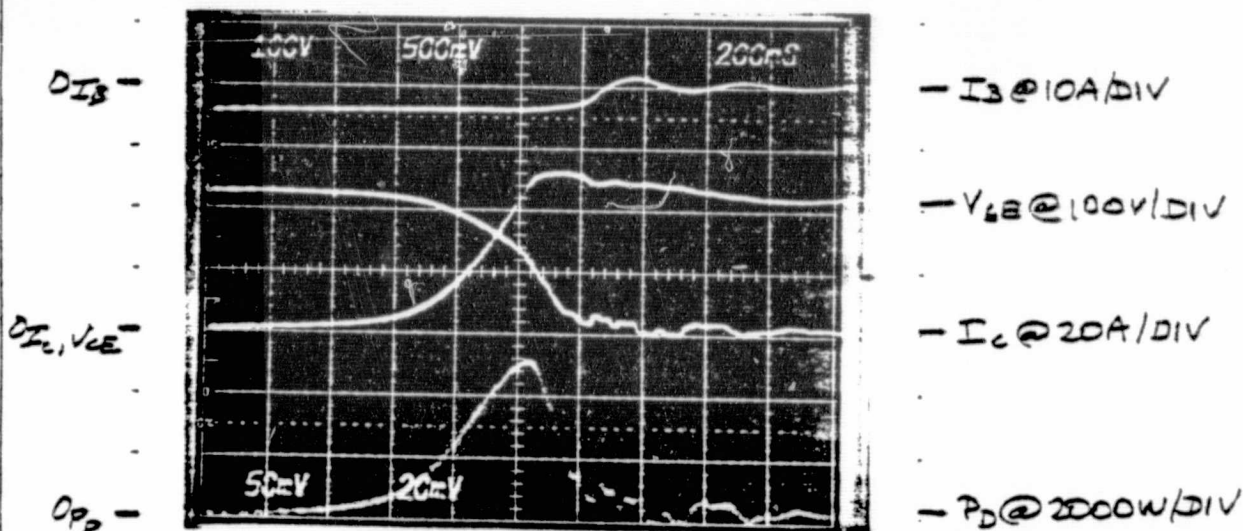
A.K. Barrett 3/4/77

D.U.T. TYPE RCA J-15490, UNIT NO. 37CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER _____

 $I_{B1} = (16 \text{ Apk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS $V_{CE} =$ 225 V PEAK, $I_C =$ 45 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %SNUBBER CONF. A6PIX NO. 3-4-B2, ADDITIONAL COMMENTS _____

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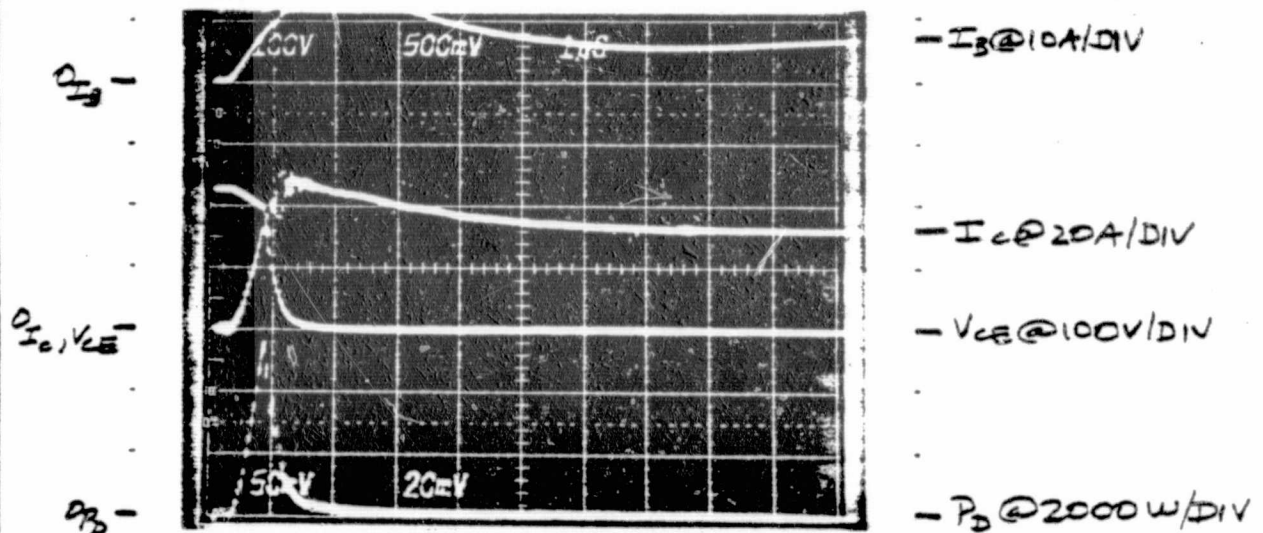
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D.U.T. TYPE RCA J-15490, UNIT NO. 37CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER _____

 $I_{B1} = (16 \text{ A pk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS $V_{CE} =$ 225 V PEAK, $I_C =$ 45 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %SNUBBER CONF. A6PIX NO. 3-4-B3, ADDITIONAL COMMENTS _____

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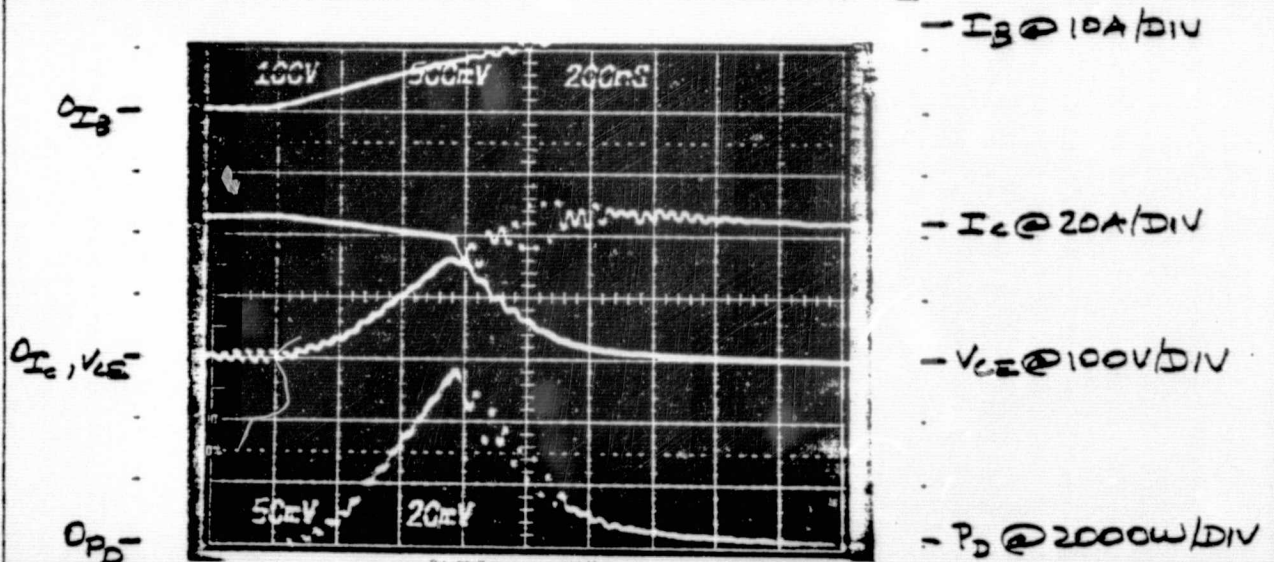
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D.U.T. TYPE RCA J-15490, UNIT NO. 37CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER

 $I_{B1} = (16 \text{ Apk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS $V_{CE} =$ 225 V PEAK, $I_C =$ 45 A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %SNUBBER CONF. A6PIX NO. 3-4-B4, ADDITIONAL COMMENTSORIGINAL PAGE IS
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D.U.T. TYPE RCA J-15490, UNIT NO. 37

CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER

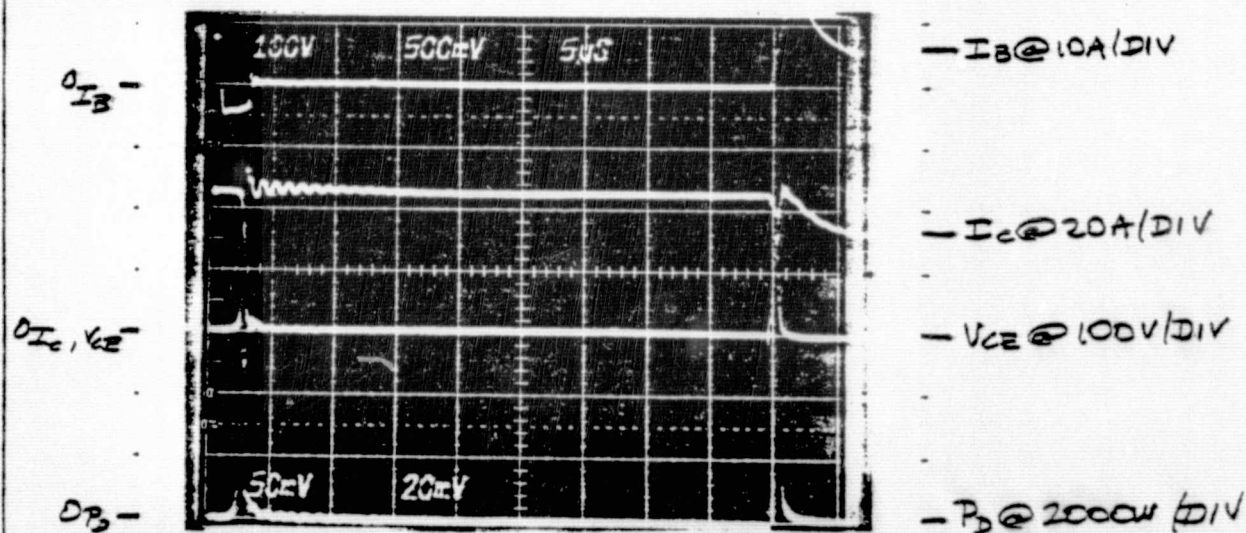
$I_{B1} = (1.6 \text{ Apk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS

$V_{CE} =$ 225 V PEAK, $I_C =$ 45 A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



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D.U.T. TYPE RCA J-15490, UNIT NO. 37

CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER

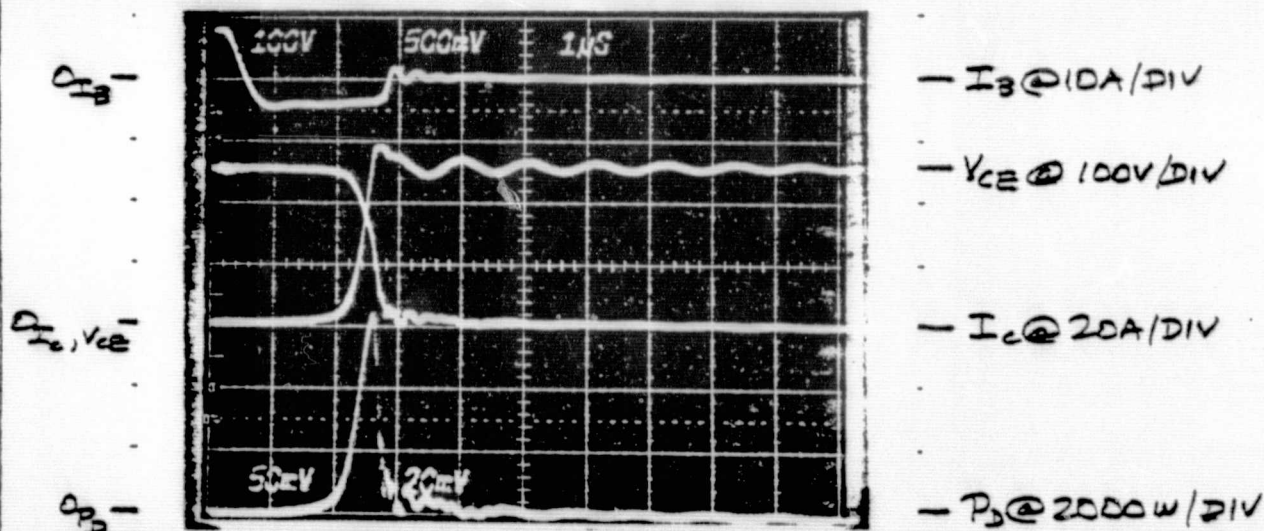
$I_{B1} = (16 \text{ Apk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



PIX NO. 3-4-C1, ADDITIONAL COMMENTS

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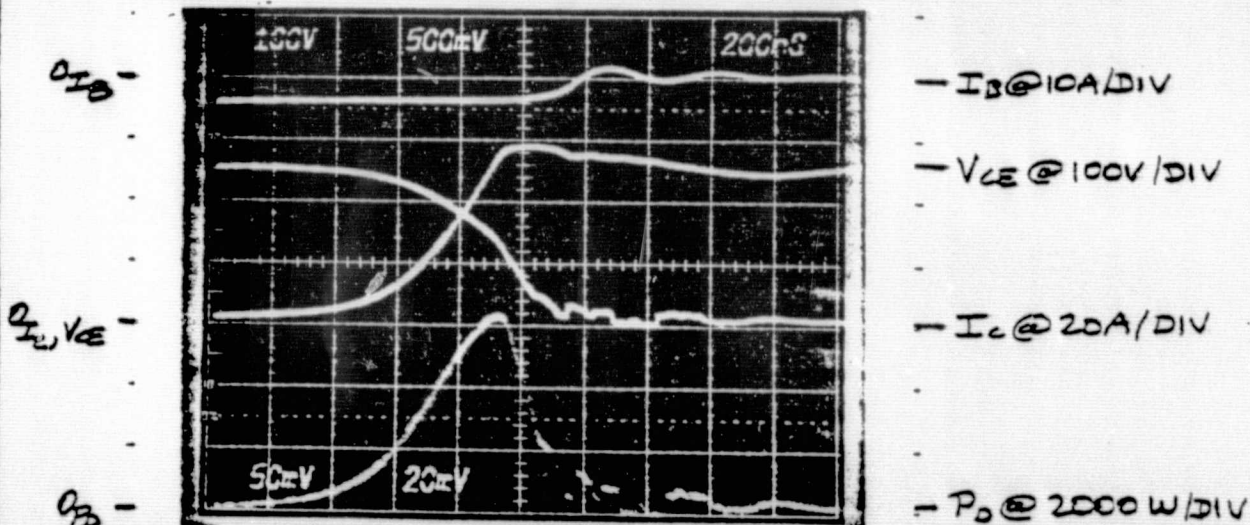
A.H. Barnett 3/4/77

D.U.T. TYPE RCA J-15490, UNIT NO. 37CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER

 $I_{B1} = (16 \text{ A pk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS $V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %SNUBBER CONF. A6PIX NO. 3-4-C2, ADDITIONAL COMMENTS

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DEVICE TESTS

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D.U.T. TYPE RCA J-15490, UNIT NO. 37

CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTIER _____

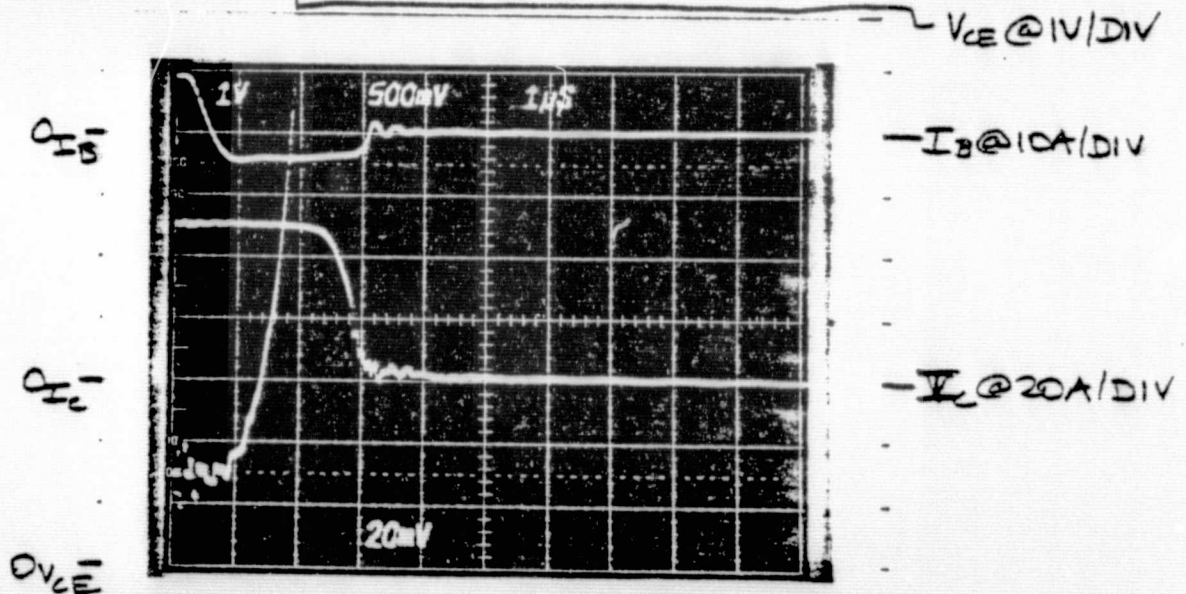
$$I_{B1} = (1.64 \mu A) \quad 9 \text{ AMPS}, \quad -I_{B2} = (-7.5 V) \quad 5 \text{ AMPS}$$

$V_{CE} = \underline{250} \text{ V PEAK}, \quad I_C = \underline{50} \text{ A PEAK}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



PIX NO. 3-4-C3, ADDITIONAL COMMENTS T_{CASE} = 35°C

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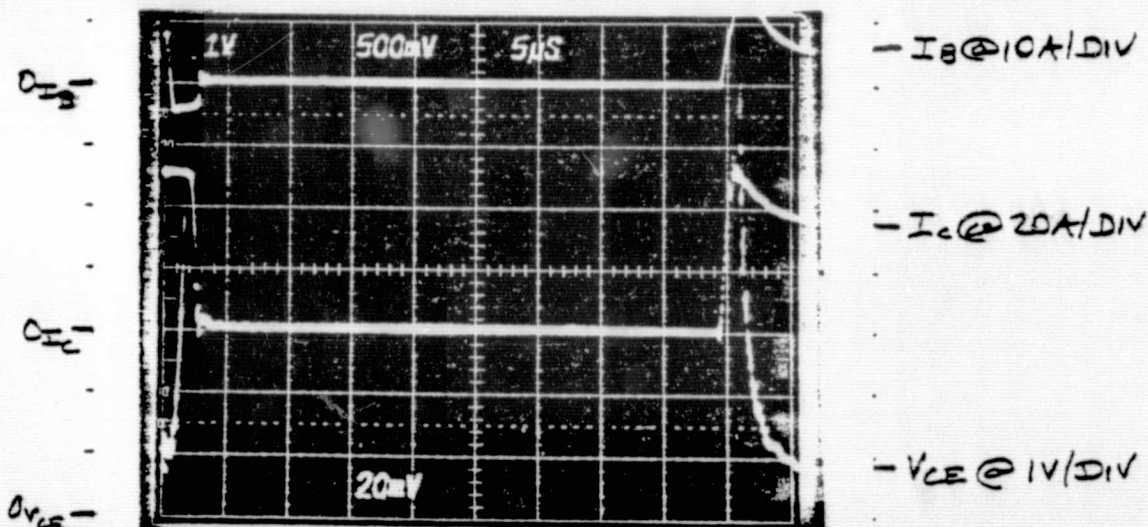
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D.U.T. TYPE RCA J-15490, UNIT NO. 37CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER _____

 $I_{B1} = (1.4 \mu k) \quad 8 \text{ AMPS}, \quad -I_{B2} = (\approx -7.5V) \quad 5 \text{ AMPS}$ $V_{CE} = \quad 250 \text{ V PEAK}, \quad I_C = \quad 50 \text{ A PEAK}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80%SNUBBER CONC. A6PIX NO. 3-4-C4, ADDITIONAL COMMENTS _____

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POWER CIRCUIT
DEVICE TESTS

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D.U.T. TYPE PCA J-15490, UNIT NO. 37

CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER

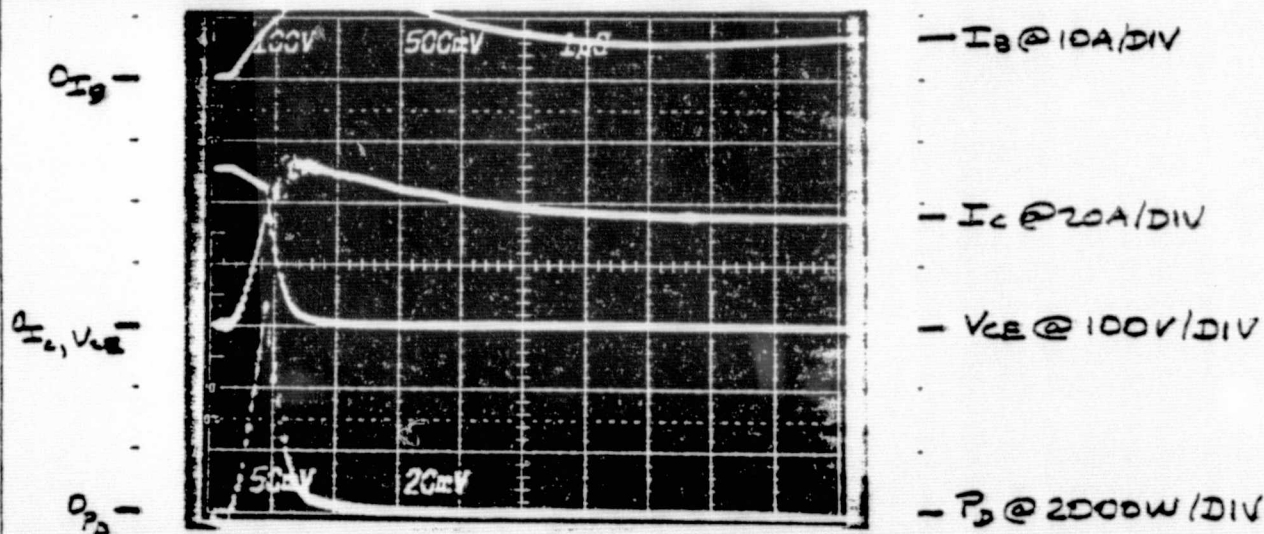
$I_{B1} = (16 \text{ Apk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



PIX NO. 3-4-C5, ADDITIONAL COMMENTS

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D.U.T. TYPE RCA J-15490, UNIT NO. 37

CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER

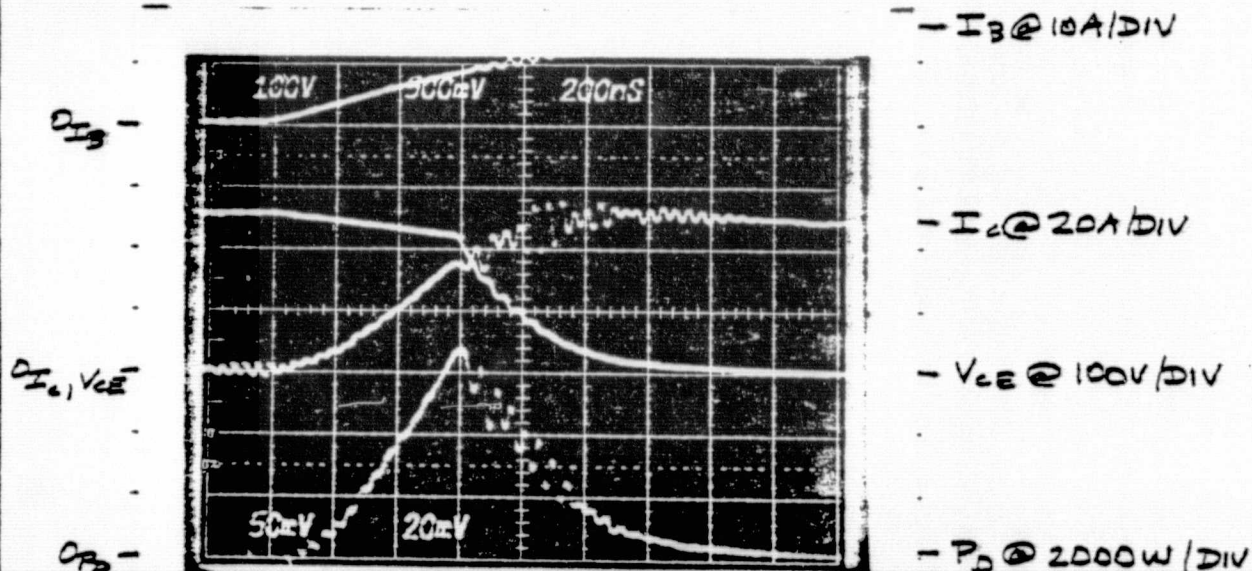
$I_{B1} = (16A_{pk})$ 8 AMPS, $-I_{B2} = (= -7.5V)$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 80%

SNUBBER CONF. A6



PIX NO. 3-4-C6, ADDITIONAL COMMENTS

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A.H. Barnett 3/4/77

D.U.T. TYPE RCA J-15490, UNIT NO. 37

CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER

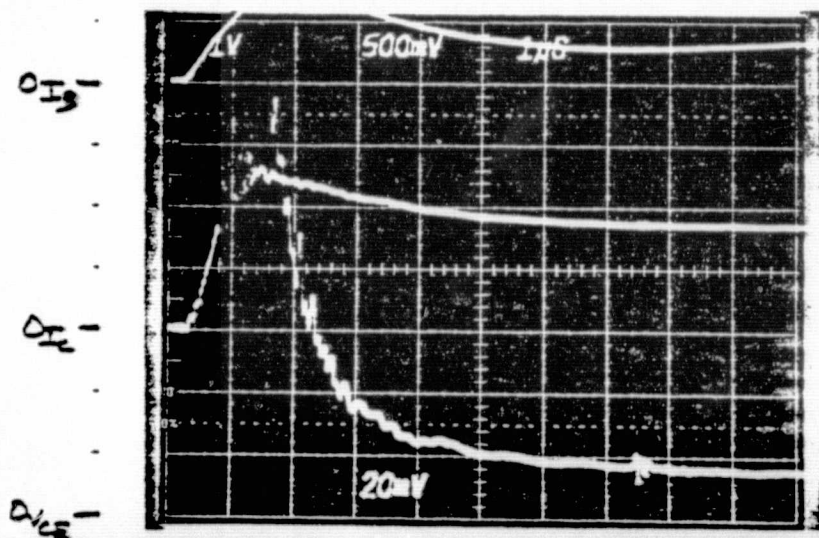
$I_{B1} = (16 \text{ Apk})$ 8 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER

FREQUENCY 4 KHZ, DUTY CYCLE ON 80%

SNUBBER CONF. A6



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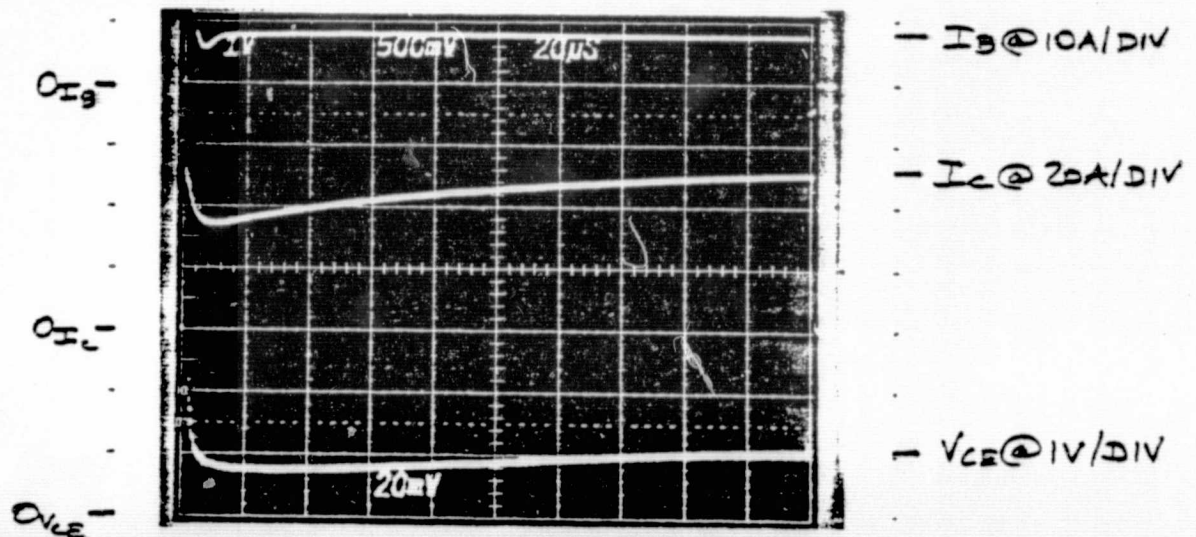
A.K. Barnett 3/4/77

D.U.T. TYPE RCA J-15490, UNIT NO. 37CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER _____

 $I_{B1} =$ (16 A pk) 8 AMPS, $-I_{B2} =$ ($\approx$ -7.5V) 5 AMPS $V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %SNUBBER CONF. A6PIX NO. 3-4-C8, ADDITIONAL COMMENTS _____

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DATE

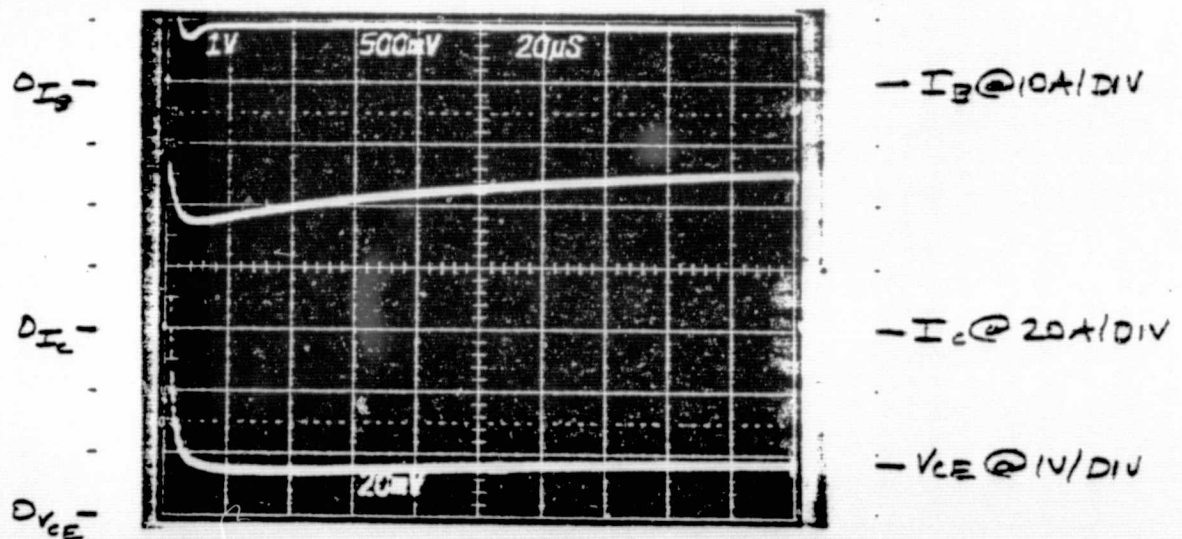
A.K. Barrett 3/4/77

D.U.T. TYPE RCA J-15490, UNIT NO. 37CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER _____

 $I_{B1} = (16 \text{ Apk})$ 9 AMPS, $-I_{B2} = (\approx -7.5 \text{ V})$ 5 AMPS $V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80%SNUBBER CONF. A6PIX NO. 3-4-C9, ADDITIONAL COMMENTS _____

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TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

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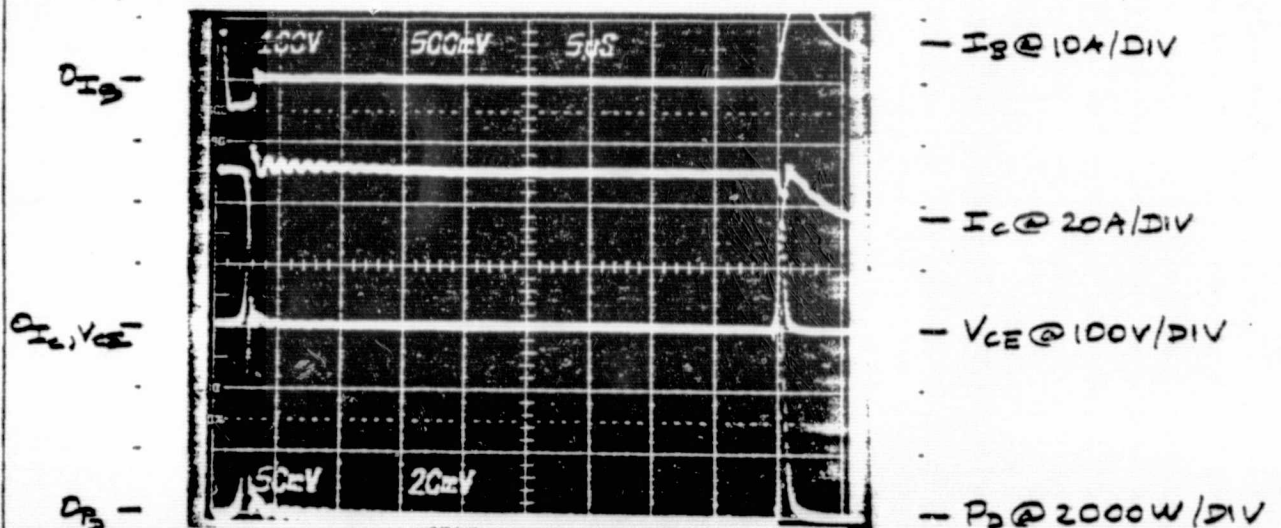
APPROVED

D.U.T. TYPE RCA J-15490, UNIT NO. 37CIRCUIT NO COLLECTOR ANTISATURATION CLAMP

OTHER _____

 $I_{B1} = (16A_{pk})$ 8 AMPS, $-I_{B2} = (\approx -7.5V)$ 5 AMPS $V_{CE} =$ 250 V PEAK, $I_C =$ 50 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80%SNUBBER CONF. A6PIX NO. 3-4-C10, ADDITIONAL COMMENTS _____

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TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

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D.U.T. TYPE WEST 178-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

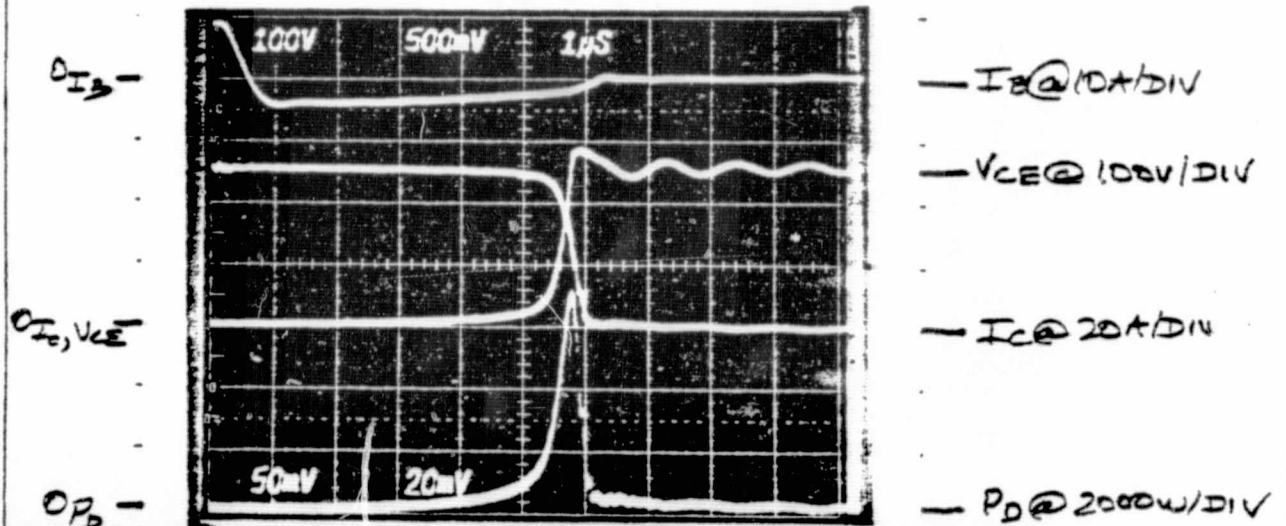
$I_{B1} =$ (18 A pk) 9 AMPS, $-I_{B2} =$ (-8.5V) 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 52 A PEAK

OTHER _____

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %

SNUBBER CONF. A6



PIX NO. 2-25-A, ADDITIONAL COMMENTS $T_{case} = 35^{\circ}C$

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POWER CIRCUIT
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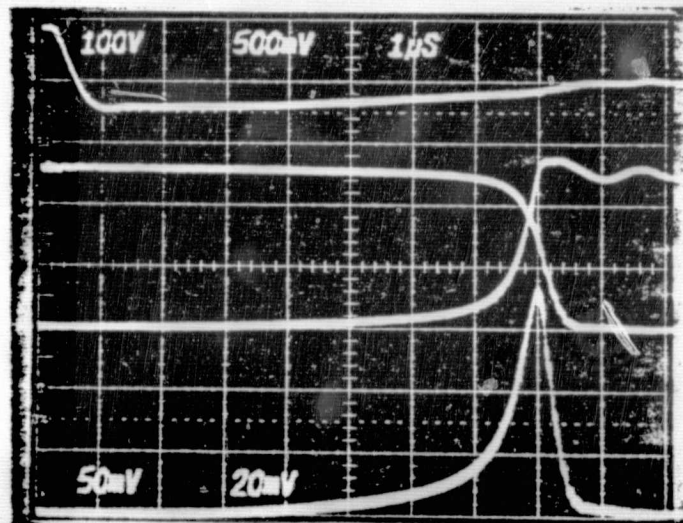
D.U.T. TYPE WEST 178-6UNIT NO. 6

CIRCUIT

OTHER

 $I_{B1} = (18 \text{ A pk})$ 9 AMPS, $-I_{B2} = (-8.5 \text{ V})$ 5 AMPS $V_{CE} =$ 250 V PEAK, $I_C =$ 52 A PEAK

OTHER

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %SNUBBER CONF. A6 O_{I_B} $O_{I_C, V_{CE}}$ O_{P_D}  $-I_B @ 10 \text{ A/DIV}$ $-V_{CE} @ 100 \text{ V/DIV}$ $-I_C @ 20 \text{ A/DIV}$ $-P_D @ 2000 \text{ W/DIV}$

PIX NO.

2-25-B

ADDITIONAL COMMENTS

 $T_{case} = 85^\circ \text{C}^+$

Takes several seconds for T_{case} to reach 85°C - stabilization would occur much higher

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barrett</i>	DATE 2-25-77
		CHECKED	
		APPROVED	

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

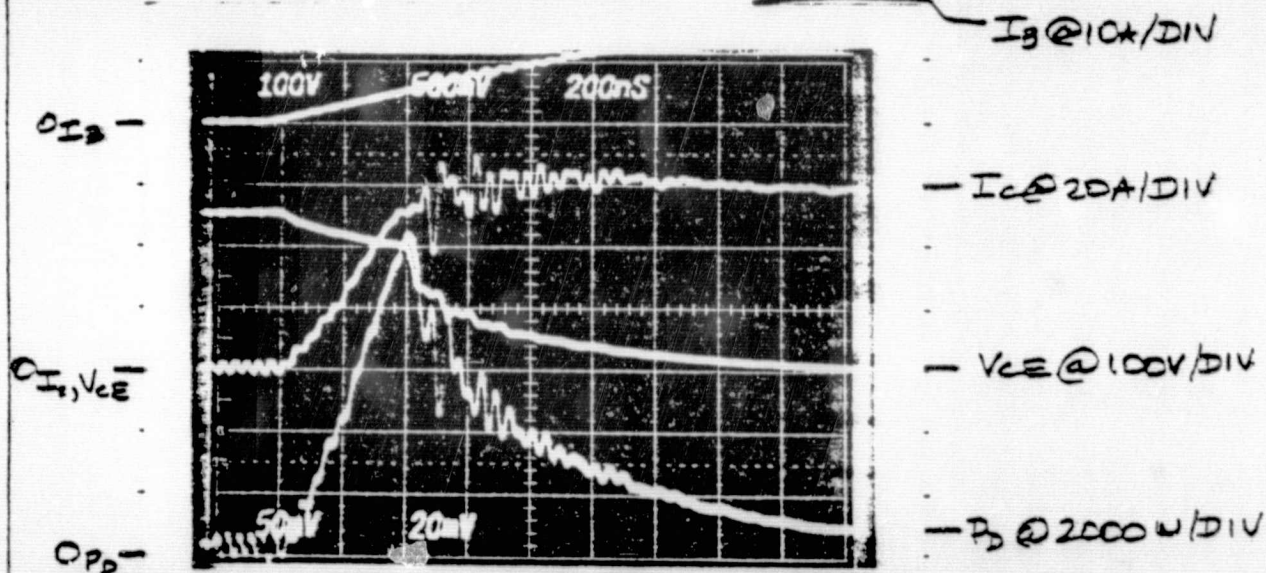
$I_{B1} = (18 \text{ A pk})$ 9 AMPS, $-I_{B2} = (-8.5 \text{ V})$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 52 A PEAK

OTHER _____

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %

SNUBBER CONF. A6



PIX NO. 2-25-C, ADDITIONAL COMMENTS $T_{case} = 35^\circ \text{C}$

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DEVICE TESTS

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G.H. Barlett 2-25-77

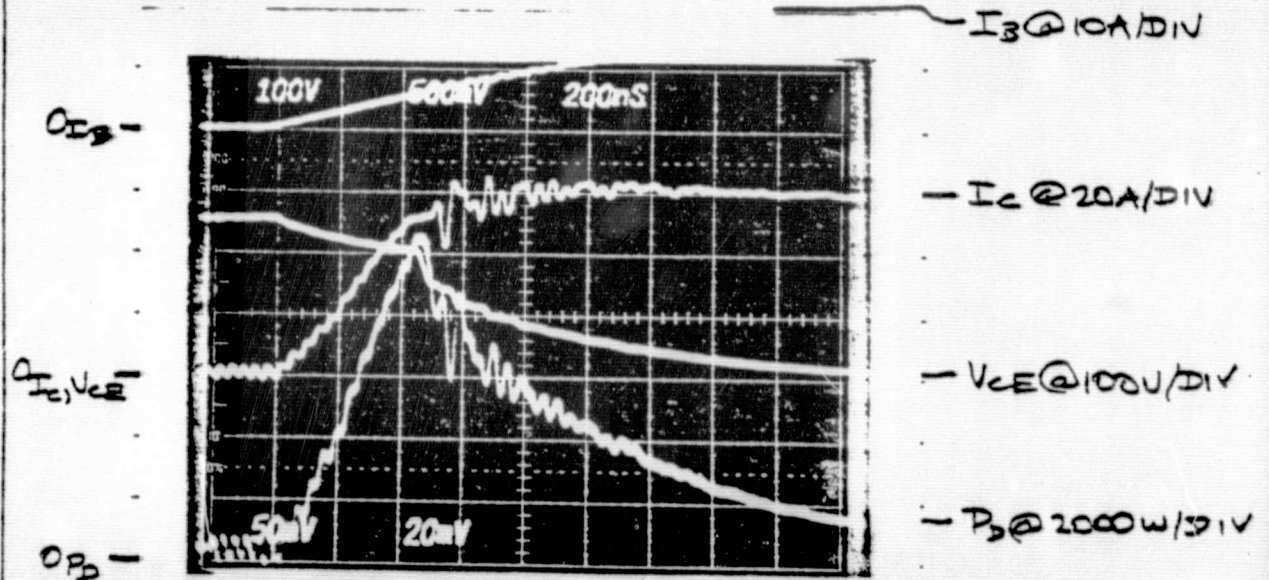
D.U.T. TYPE WEST. 178-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

 $I_{B1} = (18 \text{ A pk})$ 9 AMPS, $-I_{B2} = (-8.5 \text{ V})$ 5 AMPS $V_{CE} =$ 250 V PEAK, $I_C =$ 52 A PEAK

OTHER _____

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %SNUBBER CONF. A6PIX NO. 2-25-D, ADDITIONAL COMMENTS $T_{case} = 85^\circ \text{C} +$

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TITLE

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DEVICE TESTS

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A.H. Barrett 2-25-77

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D.U.T. TYPE WEST 178-b, UNIT NO. 6

CIRCUIT _____

OTHER _____

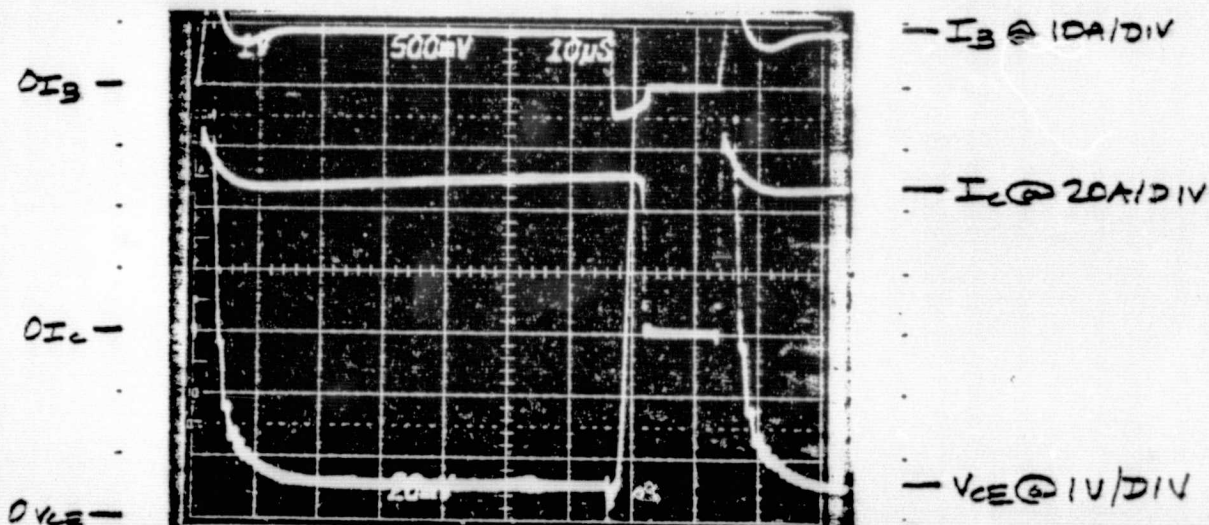
$I_{B1} = (18 \text{ Apk})$ 9 AMPS, $-I_{B2} = (-8.5 \text{ V})$ 5 AMPS

$V_{CE} =$ 250 V PEAK, $I_C =$ 52 A PEAK

OTHER _____

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %

SNUBBER CONF. A6



PIX NO. 2-25-E, ADDITIONAL COMMENTS $T_{case} = 35^\circ \text{C}$

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		CHECKED		
		APPROVED		

D.U.T. TYPE WEST 178-b, UNIT NO. 6

CIRCUIT _____

OTHER _____

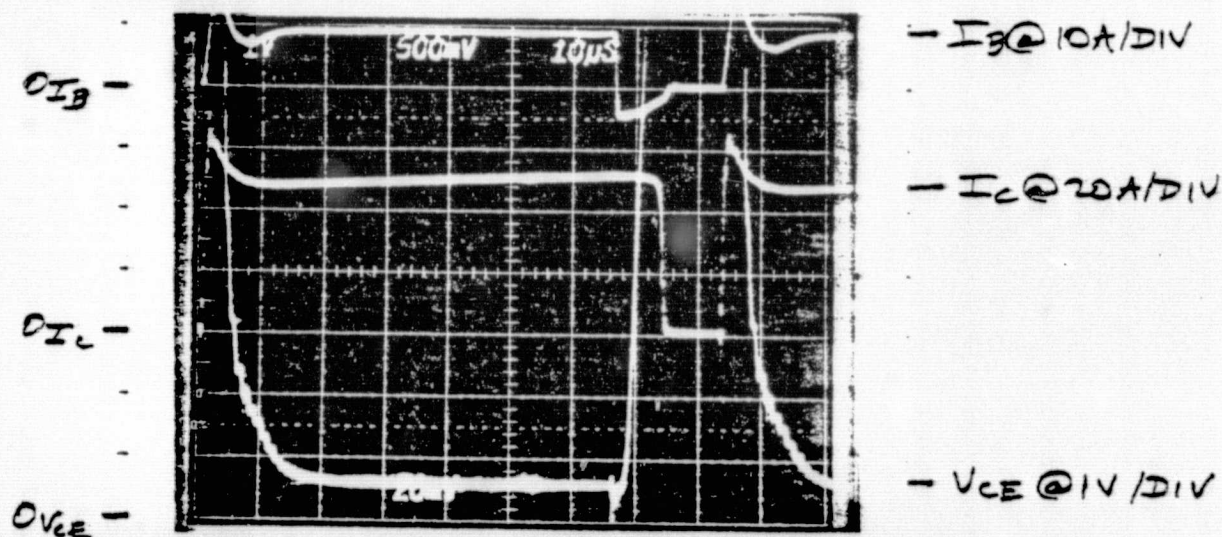
$I_{B1} = (18 \text{ A pk})$ 9 AMPS, $-I_{B2} = (-8.5 \text{ V})$ 5 AMPS

$V_{CE} = 250 \text{ V PEAK}$, $I_C = 52 \text{ A PEAK}$

OTHER _____

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %

SNUBBER CONF. A6



PIX NO. 2-25-F, ADDITIONAL COMMENTS $T_{case} = 85^\circ \text{C} +$

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A. H. Barlett</i> 2-25-77 CHECKED APPROVED		

D.U.T. TYPE WEST 178-b, UNIT NO. 6

CIRCUIT _____

OTHER _____

$I_{B1} =$ (18 A pk) 9 AMPS, $-I_{B2} =$ (-8.5V) 5 AMPS

$V_{CE} =$ _____ V PEAK, $I_C =$ _____ A PEAK

OTHER _____

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %

SNUBBER CONF. A6

O_{I_B} —

$O_{I_C, V_{CE}}$ —

O_{P_D} —

— $I_B @ 10A/DIV$

— $V_{CE} @ 100V/DIV$

— $I_C @ 20A/DIV$

— $P_D @ 2000W/DIV$
note zero too high

PIX NO. 2-25-G, ADDITIONAL COMMENTS $T_{case} = 35^{\circ}C$

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POWER CIRCUIT
DEVICE TESTS

005048F

PREPARED BY J. H. Barrett DATE 2-25-77

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D.U.T. TYPE WEST. 178-b

UNIT NO. 6

CIRCUIT

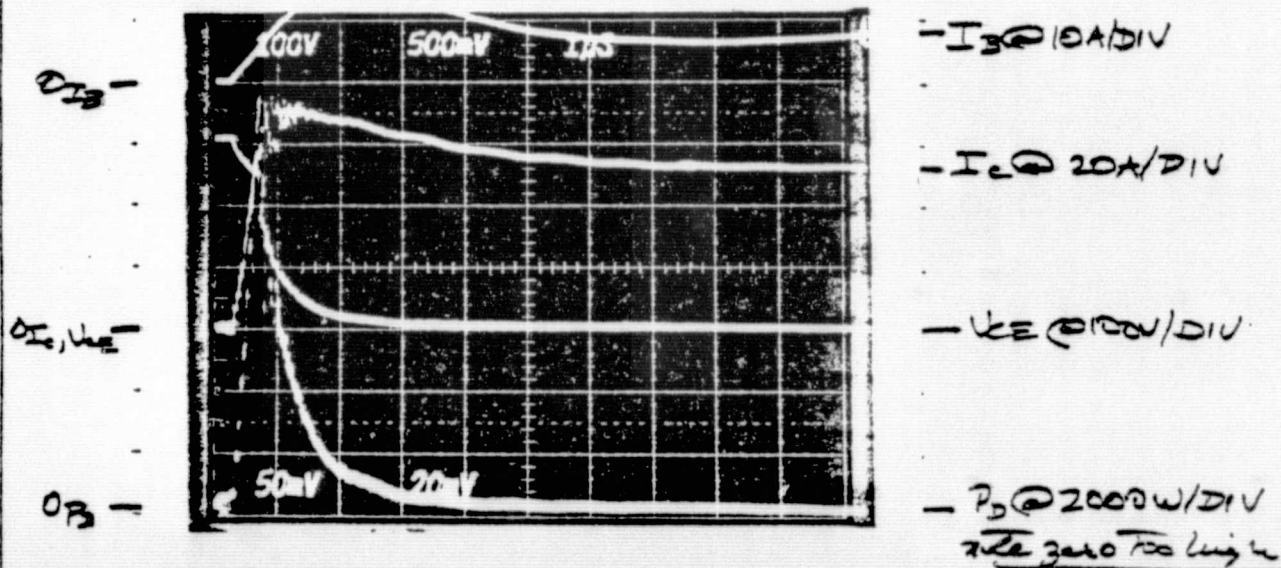
OTHER

$$I_{B1} = (18 \text{ Apk}) \quad 9 \text{ AMPS}, \quad -I_{B2} = (-8.5 \text{ V}) \quad 5 \text{ AMPS}$$
$$V_{CE} = \underline{\hspace{2cm}} \text{ V PEAK}, \quad I_C = \underline{\hspace{2cm}} \text{ A PEAK}$$

OTHER

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %

SNUBBER CONF. A6



PIX NO. 2-25-H, ADDITIONAL COMMENTS $T_{\text{case}} = 35^{\circ}\text{C}$

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TITLE

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POWER CIRCUIT
DEVICE TESTS

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D.U.T. TYPE WEST 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

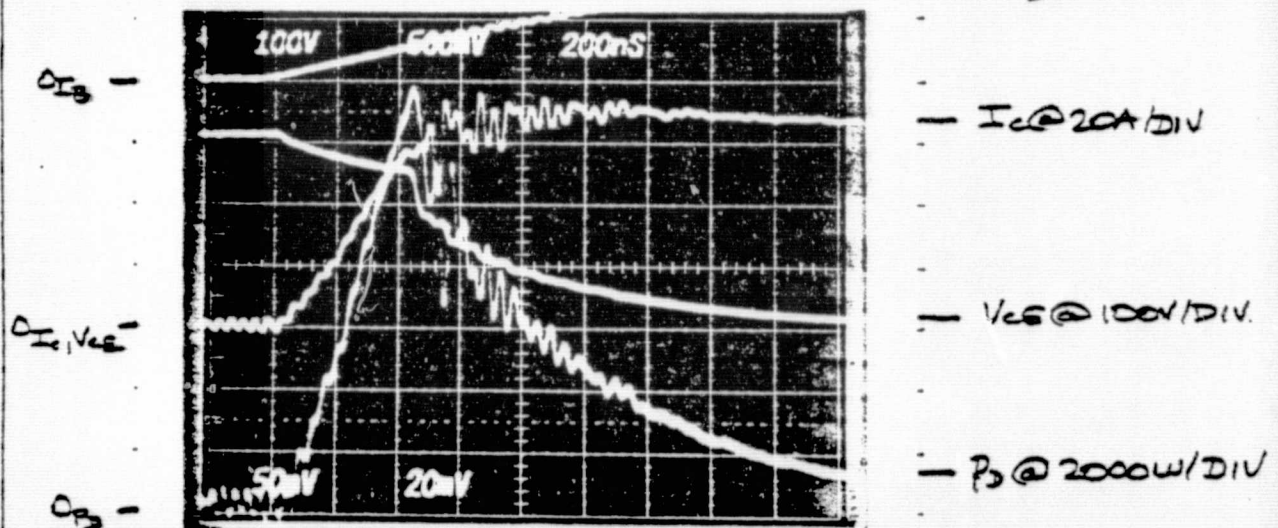
$I_{B1} =$ (18Apk) 9 AMPS, $-I_{B2} =$ (-8.5V) 5 AMPS

$V_{CE} =$ _____ V PEAK, $I_C =$ _____ A PEAK

OTHER _____

FREQUENCY 12 KHZ, DUTY CYCLE ON 80+ %

SNUBBER CONF. A6



PIX NO. 2-25-I, ADDITIONAL COMMENTS $T_{case} = 35^{\circ}C$

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>G. H. Bennett</i> 2-17-77 CHECKED APPROVED		

D.U.T. TYPE WEST 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER $R_b = 4.5\Omega$

$I_{B1} = \underline{(18A/K)} \quad 9 \text{ AMPS}, \quad -I_{B2} = \underline{(2-8V)} \quad 6 \text{ AMPS}$

$V_{CE} = \underline{275V \text{ PEAK}}, \quad I_C = \underline{60 \text{ A PEAK}}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6

$I_B @ 10A/D$

$V_{CE} @ 100V/D$

$I_C @ 20A/D$

$P_B @ 2000W/D$

PIX NO. 2-17-F, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barrett</i> 2-17-77 CHECKED APPROVED		

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

$I_{B1} =$ (18Apk) 9 AMPS, $-I_{B2} =$ (2-8V) 6 AMPS

$V_{CE} =$ 275V PEAK, $I_C =$ 60 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6

$V_{CE@1V/D}$

$-I_B@10A/D$

$-I_C@20A/D$

PIX NO. 2-17-CF, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <u>C. H. Barrett</u> DATE <u>2-17-77</u> CHECKED _____ APPROVED _____		
D.U.T. TYPE <u>WEST 17B-6</u> , UNIT NO. <u>6</u> CIRCUIT _____ OTHER _____ $I_{B1} = \underline{(18A_{pk})}$ <u>5</u> AMPS, $-I_{B2} = \underline{(2-8V)}$ <u>6</u> AMPS $V_{CE} = \underline{275V}$ PEAK, $I_C = \underline{60A}$ PEAK OTHER _____ FREQUENCY <u>4</u> KHZ, DUTY CYCLE ON <u>80</u> % SNUBBER <u>CONF. A6</u>				
I_{B1} - V_{CE}, V_E P_D - $-I_{B2} @ 10A$ $-I_C @ 20A/D$ $-V_{CE} @ 100V/D$ $-P_D @ 2000W/D$				
PIX NO. <u>2-17-H</u> , ADDITIONAL COMMENTS _____				

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TITLE

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POWER CIRCUIT
DEVICE TESTS

PREPARED

DATE

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D.U.T. TYPE WEST 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER $R_L = 4.5 \Omega$

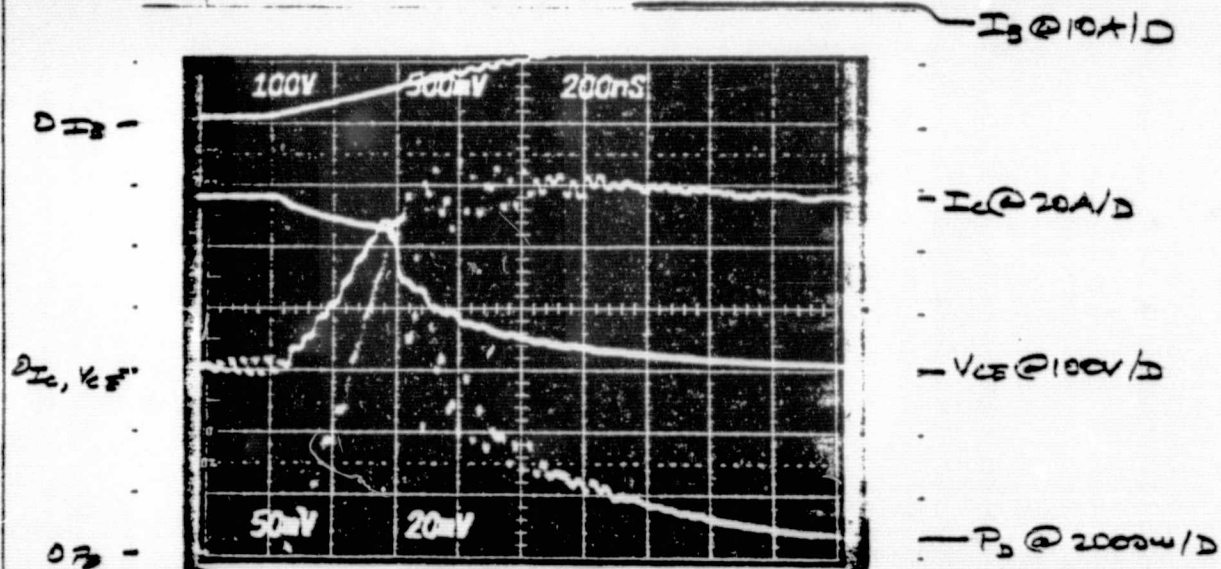
$I_{B1} =$ (18APK) 9 AMPS, $-I_{B2} =$ (2-8V) 6 AMPS

$V_{CE} =$ 275 V PEAK, $I_C =$ 60 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. AL



PIX NO. 2-17-E, ADDITIONAL COMMENTS _____

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DEVICE TESTS

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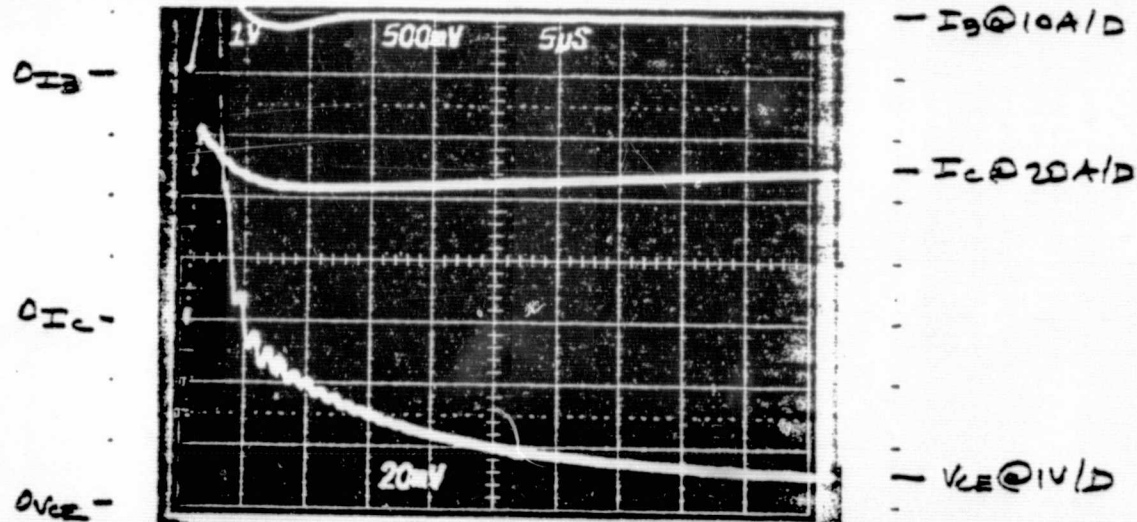
D.U.T. TYPE WEST. 17R-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

 $I_{B1} = (18Apk)$ 9 AMPS, $-I_{B2} = (2-8V)$ 6 AMPS $V_{CE} =$ 275V PEAK, $I_C =$ 60A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %SNUBBER CONF. A6PIX NO. 2-17-J, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS	PREPARED <i>A. H. Barnett</i> 2-17-77 CHECKED APPROVED		

D.U.T. TYPE WEST. 178-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

$I_{B1} = \underline{(18 \text{ Apk})}$ 9 AMPS, $-I_{B2} = \underline{(2-8 \text{ V})}$ 6 AMPS

$V_{CE} = \underline{275 \text{ V PEAK}}$, $I_C = \underline{60 \text{ A PEAK}}$

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. AB

O_{CE} -

$O_{IC, V_{CE}}$ -

O_{PD} -

- $I_B @ 10 \text{ A/D}$

- $I_C @ 20 \text{ A/D}$

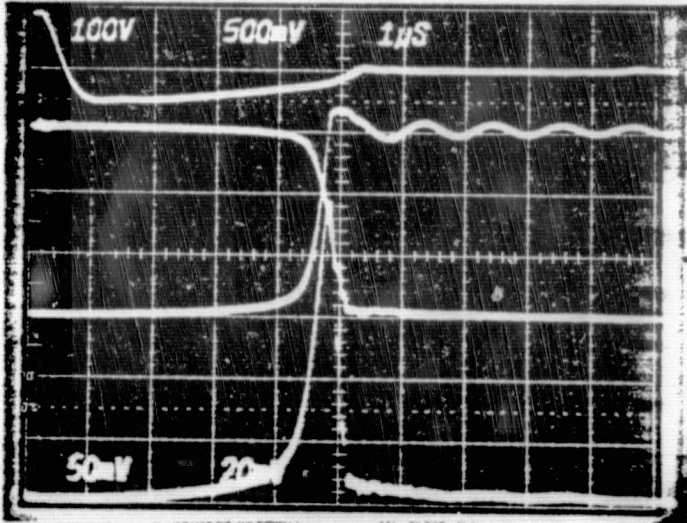
- $V_{CE} @ 100 \text{ V/D}$

- $P_D @ 2000 \text{ W/D}$

PIX NO. 2-17-K, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A. H. Barnett</i> 2-17-77 CHECKED APPROVED		
D.U.T. TYPE <u>WEST. 17B-6</u> , UNIT NO. <u>6</u> CIRCUIT _____ OTHER <u>$R_L \approx 4.8 \Omega$</u> $I_{B1} = $ <u>(18Apk)</u> <u>9</u> AMPS, $-I_{B2} = $ <u>($\approx -8V$)</u> <u>6</u> AMPS $V_{CE} = $ <u>300V</u> PEAK, $I_C = $ <u>60</u> A PEAK OTHER _____ FREQUENCY <u>4</u> KHZ, DUTY CYCLE ON <u>80</u> % SNUBBER <u>CONF AL</u>				
O_{I_B} $O_{I_C, V_{CE}}$ O_{P_D}  $- I_B @ 40A/D$ $- V_{CE} @ 100V/D$ $- I_C @ 20A/D$ $- P_D @ 2000W/D$				
PIX NO. <u>2-17-L</u> , ADDITIONAL COMMENTS _____				

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C. H. Barnett</i> 2-17-77 CHECKED APPROVED	

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

$I_{B1} =$ (18APK) 9 AMPS, $-I_{B2} =$ (2-8V) 6 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6

$O_{IB} -$

$O_{IC} -$

$O_{VCE} -$

$V_{CE} @ 1V/D$

$I_B @ 10A/D$

$I_C @ 20A/D$

PIX NO. 2-17-M, ADDITIONAL COMMENTS _____

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POWER CIRCUIT
DEVICE TESTS

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D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

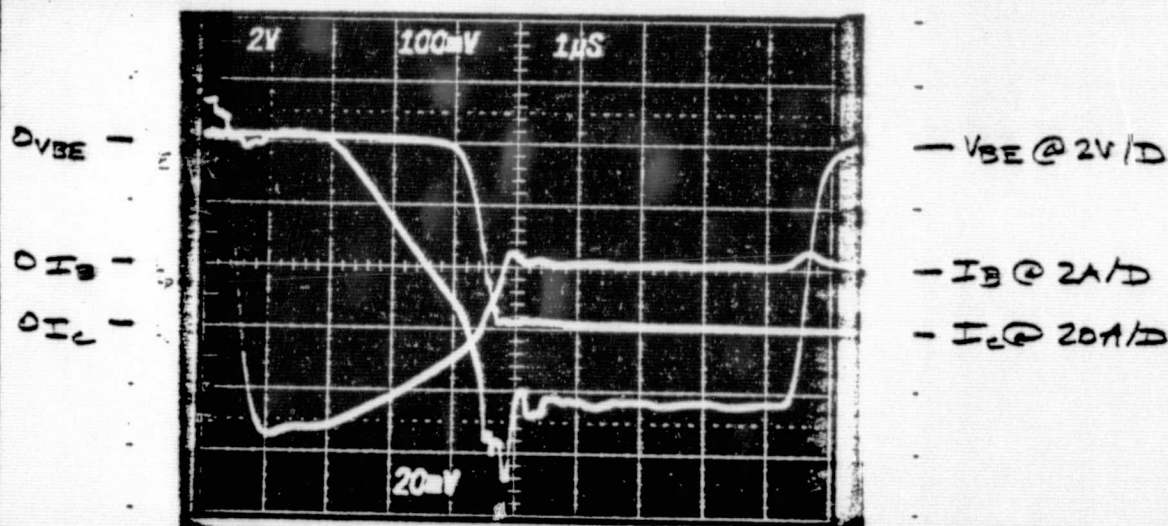
$I_{B1} =$ (18A_{pk}) 9 AMPS, $-I_{B2} =$ (-5V) 6 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF A6



PIX NO. 2-12-N, ADDITIONAL COMMENTS _____

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DEVICE TESTS

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D.U.T. TYPE WEST 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

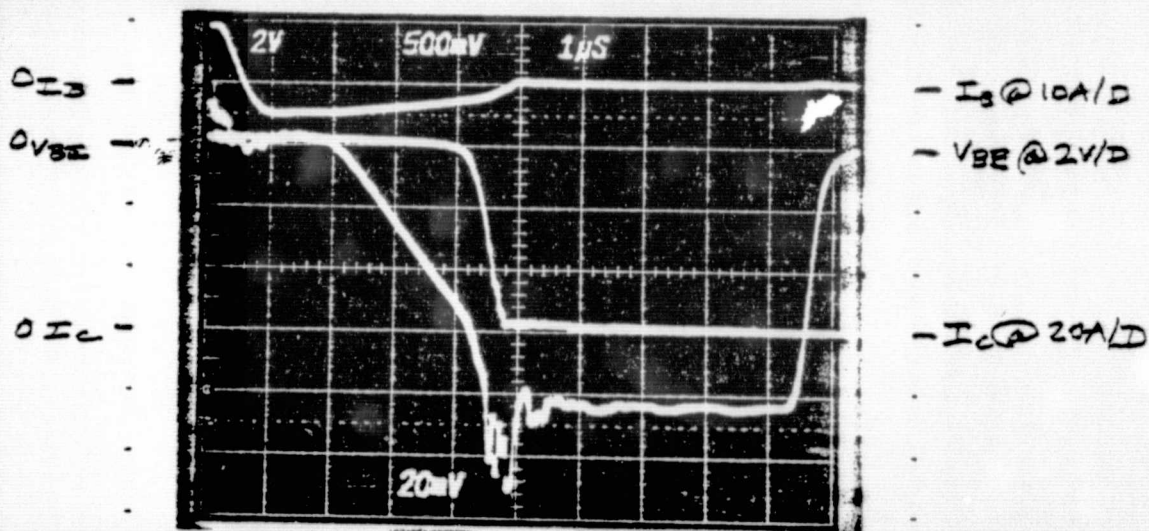
$I_{B1} = (18A_{pk})$ 7 AMPS, $-I_{B2} = (2-5V)$ 6 AMPS

$V_{CE} = 300$ V PEAK, $I_C = 60$ A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



PIX NO. 2-17-0, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS			PREPARED <i>A.H. Barnett</i>	
DATE 2-17-77			CHECKED	
APPROVED			DATE	

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

$I_{B1} =$ (18A pk) 9 AMPS, $-I_{B2} =$ ($\approx$ -8V) 6 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 80 A PEAK

OTHER _____

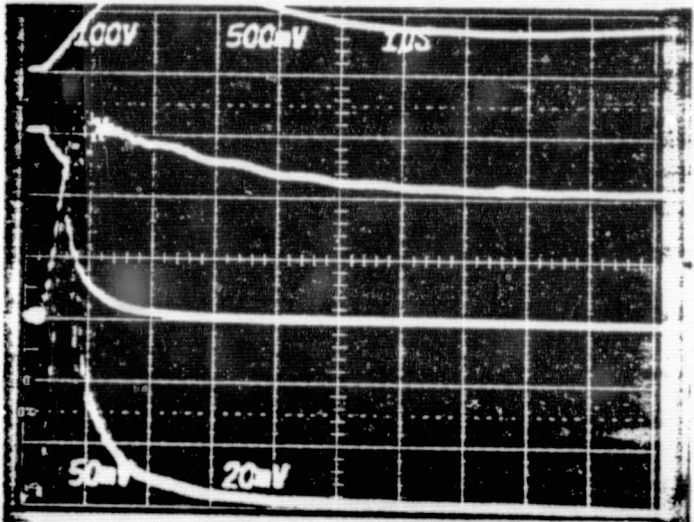
FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. AL

O_{I_B} -

$O_{I_C, V_{CE}}$

O_{P_D} -



- $I_B @ 10A/D$

- $I_C @ 20A/D$

- $V_{CE} @ 100V/D$

- $P_D @ 2000W/D$

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NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

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D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

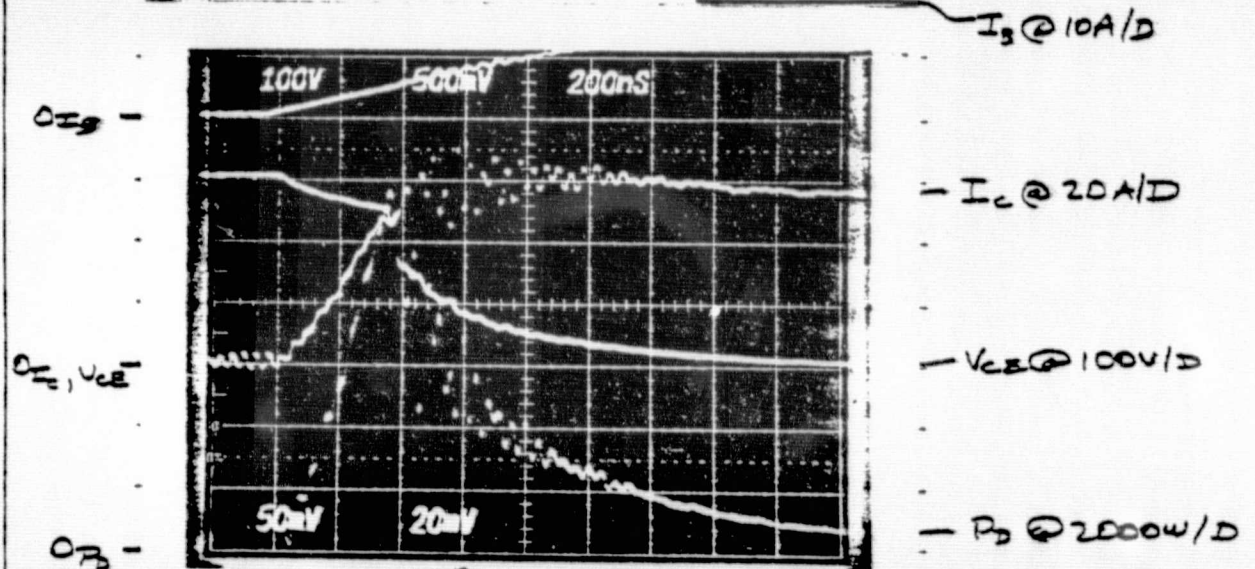
$I_{B1} =$ (18Apt) 9 AMPS, $-I_{B2} =$ ($\approx$ -8V) 6 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



PIX NO. 2-17-Q, ADDITIONAL COMMENTS _____

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE B58
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>G. H. Barrett</i> CHECKED APPROVED DATE 2-17-77		

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

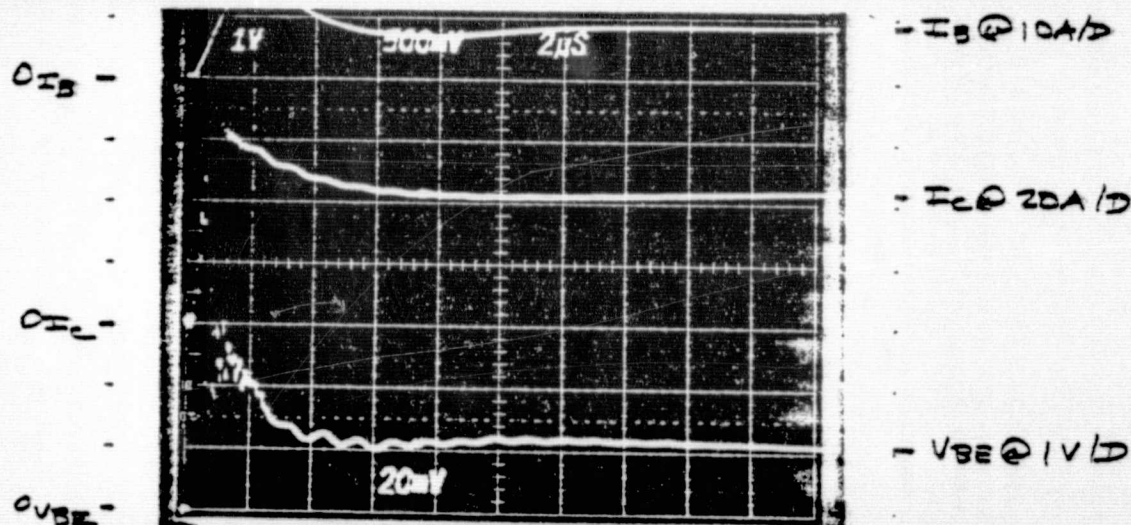
$I_{B1} = \underline{(18A \text{ pk})}$ 9 AMPS, $-I_{B2} = \underline{(\approx -8V)}$ 6 AMPS

$V_{CE} = \underline{300V}$ PEAK, $I_C = \underline{60A}$ PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



PIX NO. 2-17-R, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <u>A. H. Barrett</u> DATE <u>2-17-77</u> CHECKED _____ APPROVED _____		

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

$I_{B1} = \underline{(18A_{pk})}$ 9 AMPS, $-I_{B2} = \underline{(2-8V)}$ 6 AMPS

$V_{CE} = \underline{300}$ V PEAK, $I_C = \underline{60}$ A PEAK

OTHER _____

FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6

$O I_B$ -

$O I_C$ -

$O V_{CE}$ -

- $I_B @ 10A/D$

- $I_C @ 20A/D$

- $V_{CE} @ 1V/D$

PIX NO. 2-17-5, ADDITIONAL COMMENTS _____

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B60

TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

PREPARED

CHECKED

APPROVED

DATE

2-12-77

D.U.T. TYPE

WEST 17B-6

UNIT NO.

6

CIRCUIT

OTHER

$I_{B1} = (18A \text{ PK})$

9

AMPS,

$-I_{B2} =$

(2-8V)

6

AMPS

$V_{CE} =$

300 V PEAK,

$I_C =$

60 A PEAK

OTHER

FREQUENCY

4

KHZ,

DUTY CYCLE ON

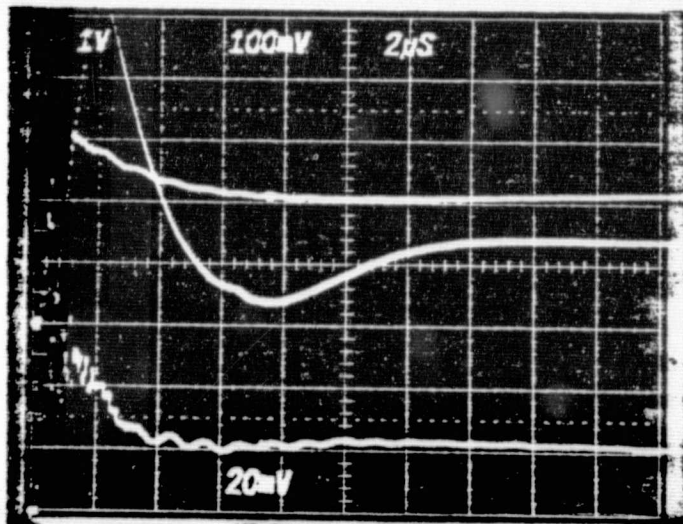
80 %

SNUBBER

CONF. AL

O_{IC}

I_B, V_{BE}



$-I_C @ 20A/D$

$-I_B @ 2A/D$

$-V_{BE} @ 1V/D$

PIX NO.

2-17-T

ADDITIONAL COMMENTS

DISTRIBUTION

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION		REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	DATE B61
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS			PREPARED <i>A.H. Barrett</i> CHECKED	DATE 2-17-77	
D.U.T. TYPE <u>WEST. 17B-6</u> , UNIT NO. <u>6</u>					
CIRCUIT _____					
OTHER _____					
$I_{B1} = (18A_{pk})$ 9 AMPS, $-I_{B2} = (2-8V)$ 6 AMPS					
$V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK					
OTHER _____					
FREQUENCY 4 KHZ, DUTY CYCLE ON 80 %					
SNUBBER <u>CONF. A6</u>					
PIX NO. <u>2-17-U</u> , ADDITIONAL COMMENTS _____					

DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE 862
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A. H. Barrett</i> 2-24-77 CHECKED APPROVED		
D.U.T. TYPE <u>WEST. 17B-6</u> , UNIT NO. <u>6</u> CIRCUIT _____ OTHER <u>$T_{CASE} = 35^{\circ}C$</u> $I_{B1} = (18 A_{pk})$ <u>7</u> AMPS, $-I_{B2} = (-8.5V)$ <u>5</u> AMPS $V_{CE} =$ <u>300</u> V PEAK, $I_C =$ <u>60</u> A PEAK OTHER _____ FREQUENCY <u>8</u> KHZ, DUTY CYCLE ON <u>80</u> % SNUBBER <u>CONF. AL</u>				
O_{I_B} - $O_{I_C, V_{CE}}$ - O_{P_D} - - $I_B @ 10A/DIV$ - $V_{CE} @ 100V/DIV$ - $I_C @ 20A/DIV$ - $P_D @ 2000W/DIV$				
PIX NO. <u>2-24-T</u> , ADDITIONAL COMMENTS _____				

DISTRIBUTION:

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>C.H. Bant</i> 2-24-77 CHECKED APPROVED		

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER $T_{CASE} = 85^{\circ}C$ (stabilized)

$I_{B1} =$ (18Apk) 9 AMPS, $-I_{B2} =$ (-8.5V) 5 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK

OTHER _____

FREQUENCY 8 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6

O_{I_B} —

$O_{I_C, V_{CE}}$ —

O_{P_D} —

— $I_B @ 10A/DIV$

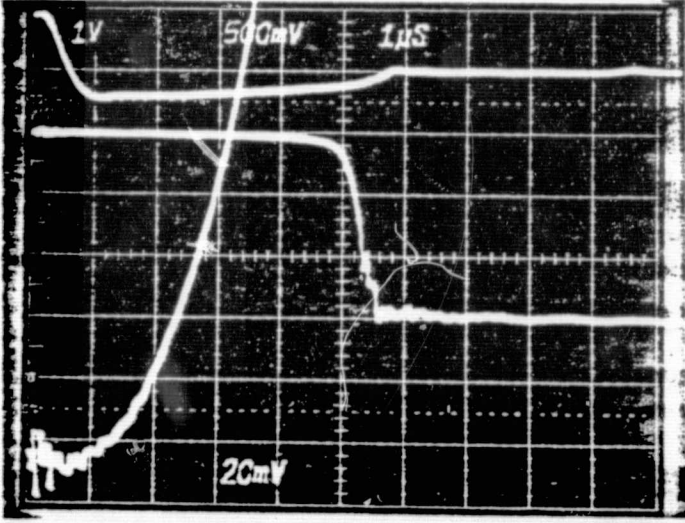
— $V_{CE} @ 100V/DIV$

— $I_C @ 20A/DIV$

— $P_D @ 2000W/DIV$

PIX NO. 2-24-U, ADDITIONAL COMMENTS _____

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE B64
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barrett</i> CHECKED APPROVED		
D.U.T. TYPE <u>WEST. 17B-6</u> , UNIT NO. <u>6</u>				
CIRCUIT _____				
OTHER <u>NOTE: $I_c = 60A$ deep saturation</u>				
$I_{B1} = $ <u>(18Apk)</u> <u>9</u> AMPS, $-I_{B2} = $ <u>(-8.5V)</u> <u>5</u> AMPS				
$V_{CE} = $ <u>300V</u> PEAK, $I_C = $ <u>60</u> A PEAK				
OTHER _____				
FREQUENCY <u>8</u> KHZ, DUTY CYCLE ON <u>80</u> %				
SNUBBER <u>CANF. AG</u>				
$V_{CE} @ 1V/DIV$ $I_B @ 10A/DIV$ $I_C @ 20A/DIV$ 				
PIX NO. <u>2-24-V</u> , ADDITIONAL COMMENTS _____				

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE B65
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS			PREPARED <i>A.H. Baird</i> 2-24-77 CHECKED APPROVED	

D.U.T. TYPE WEST 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER NOTE $I_C > 60A$ pulling out of saturation

$I_{B1} = (18A_{pk})$ 9 AMPS, $-I_{B2} = (-8.5V)$ 5 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 60⁺ A PEAK

OTHER _____

FREQUENCY 8 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6

O_{I_B} -

O_{I_C} -

$O_{V_{CE}}$ -

$V_{CE} @ 1V/DIV$

$I_B @ 10A/DIV$

$I_C @ 20A/DIV$

PIX NO. 2-24-VA, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>G.H. Barnett</i> 2-24-77 CHECKED APPROVED		
D.U.T. TYPE <u>WEST. 178-6</u> , UNIT NO. <u>6</u> CIRCUIT _____ OTHER _____ $I_{B1} = \underline{(18 \text{ Apk})}$ <u>9</u> AMPS, $-I_{B2} = \underline{(-8.5 \text{ V})}$ <u>5</u> AMPS $V_{CE} = \underline{300}$ V PEAK, $I_C = \underline{60}$ A PEAK OTHER _____ FREQUENCY <u>8</u> KHZ, DUTY CYCLE ON <u>80</u> % SNUBBER <u>CONF. AL</u>				
I_{B1} I_{B2} V_{CE} P_D $I_{B1} @ 10 \text{ A/DIV}$ $I_{B2} @ 20 \text{ A/DIV}$ $V_{CE} @ 100 \text{ V/DIV}$ $P_D @ 2000 \text{ W/DIV}$				
PIX NO. <u>2-24-W</u> , ADDITIONAL COMMENTS _____				

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <u>G. H. Barrett</u> DATE <u>2-24-77</u> CHECKED _____ APPROVED _____		

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

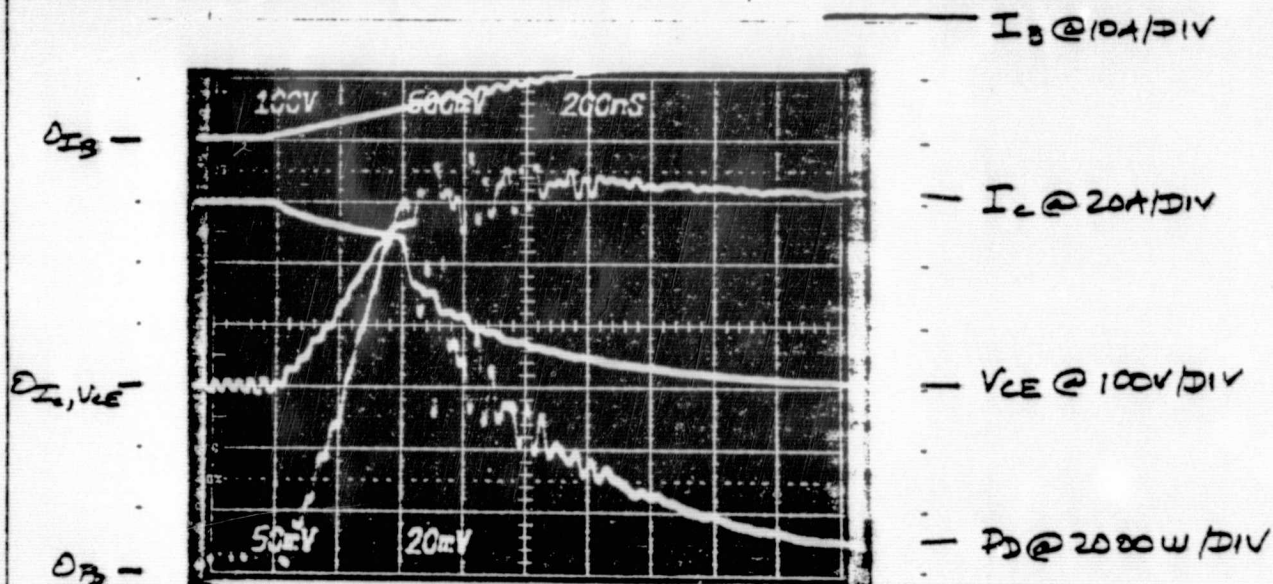
$I_{B1} = (18 \text{ Apk})$ 7 AMPS, $-I_{B2} = (-8.5 \text{ V})$ 5 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK

OTHER _____

FREQUENCY 8 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



PIX NO. 2-24-WA, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barrett</i> CHECKED DATE 2-24-77 APPROVED		

D.U.T. TYPE WEST. 178-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

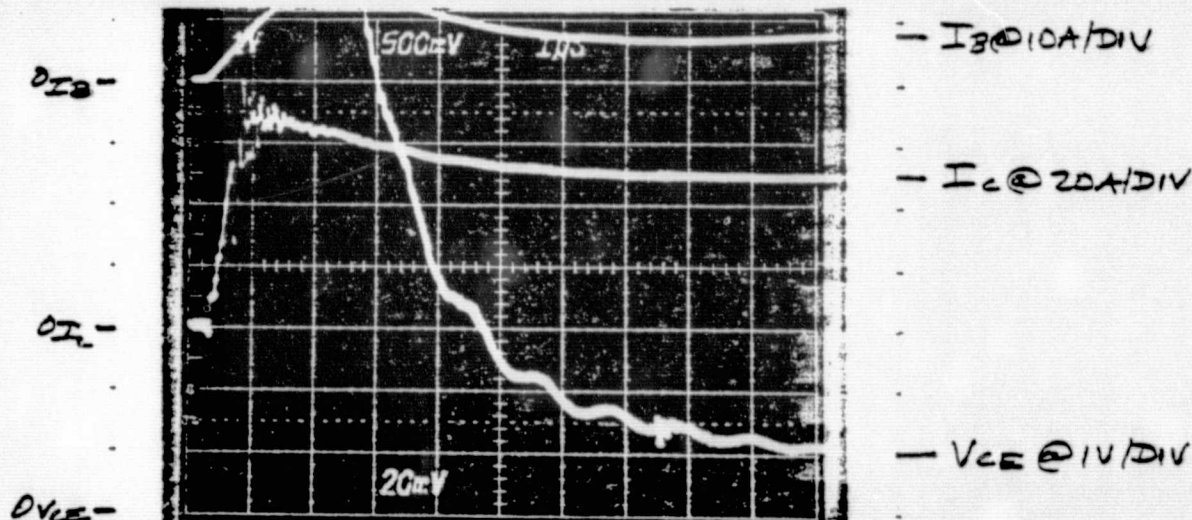
$I_{B1} = (18 \text{ Apk})$ 9 AMPS, $-I_{B2} = (-8.5V)$ 5 AMPS

$V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK

OTHER _____

FREQUENCY 8 KHZ, DUTY CYCLE ON 80 %

SNUBBER CONF. A6



PIX NO. 2-24-X, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A. H. Barrett</i> - 2-24-77 CHECKED APPROVED		

D.U.T. TYPE WEST. 178-6, UNIT NO. 6

CIRCUIT _____

OTHER _____

$I_{B1} = \underline{(18A\mu K)} \quad 9 \text{ AMPS}, \quad -I_{B2} = \underline{(-8.5V)} \quad 5 \text{ AMPS}$

$V_{CE} = \underline{300 \text{ V PEAK}}, \quad I_C = \underline{60 \text{ A PEAK}}$

OTHER _____

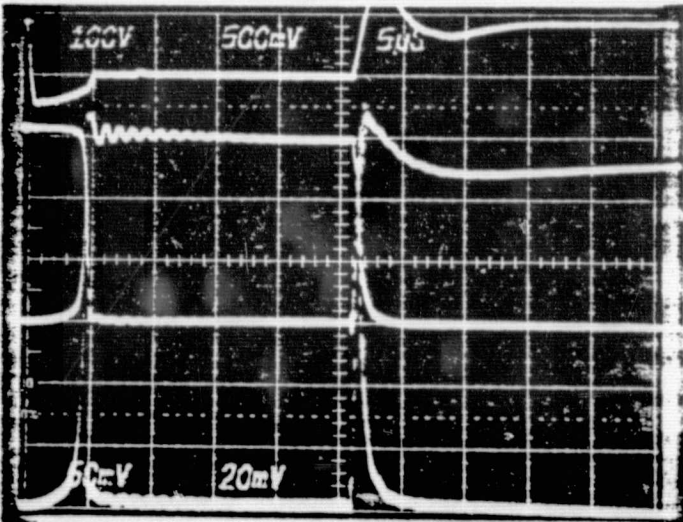
FREQUENCY 8 KHZ, DUTY CYCLE ON 80%

SNUBBER CONF. 46

O_{I_B}

 $O_{I_C, V_{CE}}$

 O_{P_D}



$- I_B @ 10A/DIV$

 $- I_C @ 20A/DIV$

 $- V_{CE} @ 100V/DIV$

 $- P_D @ 2000W/DIV$

PIX NO. 2-24-Y, ADDITIONAL COMMENTS _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>G.H. Bawert</i> 2-24-77 CHECKED APPROVED		
D.U.T. TYPE <u>WEST. 17B-6</u> , UNIT NO. <u>6</u> CIRCUIT _____ OTHER _____ $I_{B1} = (18 \text{ Apk})$ <u>9</u> AMPS, $-I_{B2} = (-8.5 \text{ V})$ <u>5</u> AMPS $V_{CE} =$ <u>300</u> V PEAK, $I_C =$ <u>60</u> A PEAK OTHER _____ FREQUENCY <u>8</u> KHZ, DUTY CYCLE ON <u>80</u> % SNUBBER <u>ONE AL</u>				
I_{B1} I_{B2} V_{CE} $I_B @ 10A/DIV$ $I_C @ 20A/DIV$ $V_{CE} @ 1V/DIV$				
PIX NO. <u>2-24-2</u> , ADDITIONAL COMMENTS _____				

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C	

ENGINEERING EXHIBIT

APPENDIX C
TEST RESULT SUMMARIES

This appendix summarizes some of the more important test results.

DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE C1
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS			PREPARED BY <u>C.H. Barrett</u> DATE <u>3/9/77</u> CHECKED _____ APPROVED _____	

D.U.T. TYPE POWERTECH, UNIT NO. 2

CIRCUIT _____

OTHER _____, $T_{CASE} < 50^{\circ}C$

REF. PIX NOS. 3-2-R1 Through 3-2-R9

$V_{CE} =$ 300 V PEAK, $I_C =$ 62 A PEAK, FREQ 4 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 3-2-R1, 3-2-B

INTERVAL (AFTER LOGIC TURN OFF) 0 μS TO 9.5 μS

1. AVERAGE POWER DISSIPATED 52 WATTS
2. PEAK POWER DISSIPATED 10000 WATTS
3. STORAGE TIME (TO 10% FALL) 3.5 μS , (I_C) OR V_{CE}
4. FALL TIME (10% TO 90%) 1.55 μS , (I_C) OR V_{CE}
5. $-dI_C/dt$ 53 A/ μS
6. $-dI_{B2}/dt$ 23 A/ μS
7. $-I_{B2}$ 4.5 A PEAK
8. $-V_{BE}$ 8 V AVERAGE
9. OTHER _____

B. TURN ON, REF. PIX NOS. 3-2-R4

INTERVAL (AFTER LOGIC TURN ON) 0 μS TO 7 μS

1. AVERAGE POWER DISSIPATED 37.8 ~~52~~ WATTS
2. PEAK POWER DISSIPATED 11,000 ~~10000~~ WATTS
3. DELAY TIME (TO 10% RISE) 0.1 μS , (I_C) OR V_{CE}
4. RISE TIME (10% TO 90%) 0.5 μS , (I_C) OR V_{CE}

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS (CONTINUED)		PREPARED <i>A.H. Barrett</i> CHECKED DATE 3/9/77 APPROVED		

5. dI_{IC}/dt 100 A/ μ s

6. dI_{BI}/dt 12 A/ μ s

7. I_{BI} 8 A AVERAGE, 16 A PEAK

8. V_{BE} — V PEAK

9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)

INTERVAL (AFTER LOGIC TURN ON) 7 μ s TO 220 μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR
 (OVER INTERVAL ABOVE) 29 WATTS

2. AVERAGE POWER DISSIPATED IN BASE
 (OVER TOTAL ON INTERVAL) 6.8 WATTS

3. V_{BE} 1.0 V @ I_{BI} 8 A

4. PERCENT ON TIME 85 %

5. V_{CE} .55 V @ I_C 62 A

6. OTHER _____

D. SUMMARY OF LOSSES

1. TURN OFF 52 WATTS

2. TURN ON 37.8 WATTS

3. QUASISTATIC ON 35.8 WATTS

4. TOTAL LOSSES 125.6 WATTS

E. COMMENTS: _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <u>A. H. Bennett</u> 2/23/77 CHECKED APPROVED		

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6
 CIRCUIT WITHOUT CLAMP
 OTHER _____, T_{CASE} < 50 °C
 REF. PIX NOS. 2-17-L, M, N, O, P, Q, R, S, T, U
 $V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK, FREQ 4 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 2-17-N, 2-17-L
 INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 30.2 WATTS
2. PEAK POWER DISSIPATED 7800 WATTS
3. STORAGE TIME (TO 10% FALL) 3.6 μ S, (I_C) OR V_{CE}
4. FALL TIME (10% TO 90%) 0.7 μ S, (I_C) OR V_{CE}
5. $-dI_C/dt$ 75 A/ μ S
6. $-dI_{B2}/dt$ 23 A/ μ S
7. $-I_{B2}$ 5 A PEAK
8. $-V_{BE}$ 8.5 V AVERAGE
9. OTHER _____

B. TURN ON, REF. PIX NOS. 2-17-P - 2-17-T
 INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 7 μ S

1. AVERAGE POWER DISSIPATED 35.9 WATTS
2. PEAK POWER DISSIPATED 11,500 WATTS
3. DELAY TIME (TO 10% RISE) 0.1 μ S, (I_C) OR V_{CE}
4. RISE TIME (10% TO 90%) 0.4 μ S, (I_C) OR V_{CE}

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS (CONTINUED)		PREPARED <i>C.H. Barlett</i> 2/23/77 CHECKED APPROVED		

5. dI_{IC}/dt 150 A/ μ s

6. dI_{BI}/dt 12 A/ μ s

7. I_{BI} 9 A AVERAGE, 17 A PEAK

8. V_{BE} 2.5 V PEAK

9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)

INTERVAL (AFTER LOGIC TURN ON) 7 μ s TO 207 μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR
 (OVER INTERVAL ABOVE) 40.3 WATTS

2. AVERAGE POWER DISSIPATED IN BASE
 (OVER TOTAL ON INTERVAL) 9.2 WATTS

3. V_{BE} 1.2 V @ I_{BI} 9 A

4. PERCENT ON TIME 80 %

5. V_{CE} .84 V @ I_C 60 A

6. OTHER C. TOTAL 49.5 W

D. SUMMARY OF LOSSES

1. TURN OFF 30.2 WATTS

2. TURN ON 35.9 WATTS

3. QUASISTATIC ON 49.5 WATTS

4. TOTAL LOSSES 115.6 WATTS

E. COMMENTS: _____

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TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

PREPARED

CHECKED

APPROVED

DATE

A.H. Barrett 3/9/77

D.U.T. TYPE RCA J-15490, UNIT NO. 37

CIRCUIT _____

OTHER _____, T_{CASE} < 35 °C

REF. PIX NOS. 3-4-C1 Through 3-4-C10

V_{CE} = 250 V PEAK, I_C = 50 A PEAK, FREQ 4 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 3-4-C1 and C2

INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 11.0 WATTS

2. PEAK POWER DISSIPATED 6100 WATTS

3. STORAGE TIME (TO 10% FALL) 1.8 μ S, (I_C) OR V_{CE}

4. FALL TIME (10% TO 90%) 0.6 μ S, (I_C) OR V_{CE}

5. $-dI_C/dt$ 125 A/ μ S

6. $-dI_{B2}/dt$ 23 A/ μ S

7. $-I_{B2}$ 4.5 A PEAK

8. $-V_{BE}$ 7.5 V AVERAGE

9. OTHER _____

B. TURN ON, REF. PIX NOS. 3-4-C5 and C6

INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 14.5 WATTS

2. PEAK POWER DISSIPATED 6600 WATTS

3. DELAY TIME (TO 10% RISE) 0.2 μ S, (I_C) OR V_{CE}

4. RISE TIME (10% TO 90%) 0.5 μ S, (I_C) OR V_{CE}

TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS (CONTINUED)

PREPARED A. H. Bennett DATE 3/5/77
CHECKED _____
APPROVED _____

5. dI_C/dt 77 A/ μ s
6. dI_{B1}/dt 12 A/ μ s
7. I_{B1} 9 A AVERAGE, 18 A PEAK
8. V_{BE} _____ V PEAK
9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)

INTERVAL (AFTER LOGIC TURN ON) 10 μ s TO 210 μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR
(OVER INTERVAL ABOVE) 60 WATTS
2. AVERAGE POWER DISSIPATED IN BASE
(OVER TOTAL ON INTERVAL) 8.6 WATTS
3. V_{BE} 1.2 V @ I_{B1} 9 A
4. PERCENT ON TIME 80 %
5. V_{CE} 1.50 V @ I_C 50 A
6. OTHER _____

D. SUMMARY OF LOSSES

1. TURN OFF 11.0 WATTS
2. TURN ON 14.5 WATTS
3. QUASISTATIC ON 68.6 WATTS
4. TOTAL LOSSES 94.1 WATTS

E. COMMENTS: question - Why such high V_{CE} ?
answer - device pulling out of saturation
at elevated (above curve tracer testing)
junction temperature

DELCO ELECTRONICS
GENERAL MOTORS CORPORATION

EE-22T-EMA-022

C7

TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

PREPARED

CHECKED

APPROVED

DATE

C. H. Barrett 3/9/77

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT

OTHER _____, T_{CASE} 635 °C

REF. PIX NOS. 2-17-A through 2-17-E

V_{CE} = 250 V PEAK, I_C = 55 A PEAK, FREQ 4 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 2-17-A

INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 17.8 WATTS

2. PEAK POWER DISSIPATED 7400 WATTS

3. STORAGE TIME (TO 10% FALL) 4.2 μ S, I_C OR V_{CE}

4. FALL TIME (10% TO 90%) 0.55 μ S, I_C OR V_{CE}

5. $-dI_C/dt$ 114 A/ μ S

6. $-dI_{B2}/dt$ 23 A/ μ S

7. $-I_{B2}$ 5 A PEAK

8. $-V_{BE}$ 8 V AVERAGE

9. OTHER _____

B. TURN ON, REF. PIX NOS. 2-17-C and CA

INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 23 WATTS

2. PEAK POWER DISSIPATED 9200 WATTS

3. DELAY TIME (TO 10% RISE) 0.08 μ S, I_C OR V_{CE}

4. RISE TIME (10% TO 90%) 0.4 μ S, I_C OR V_{CE}

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TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS (CONTINUED)

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G. H. Barnett 3/9/77

5. dI_C/dt 144 A/ μ s6. dI_{B1}/dt 12 A/ μ s7. I_{B1} 8 A AVERAGE, 16 A PEAK8. V_{BE} _____ V PEAK

9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)INTERVAL (AFTER LOGIC TURN ON) 10 μ s TO 210 μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR

(OVER INTERVAL ABOVE) 26.4 WATTS

2. AVERAGE POWER DISSIPATED IN BASE

(OVER TOTAL ON INTERVAL) 7 WATTS3. V_{BE} 1.1 V @ I_{B1} 8 A4. PERCENT ON TIME 80 %5. V_{CE} 0.6 V @ I_C 55 A

6. OTHER _____

D. SUMMARY OF LOSSES1. TURN OFF 17.8 WATTS2. TURN ON 23 WATTS3. QUASISTATIC ON 33.4 WATTS4. TOTAL LOSSES 74.2 WATTS

E. COMMENTS: _____

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TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS

PREPARED
A. H. Barnett
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DATE

2-24-77

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D.U.T. TYPE WEST 17B-6, UNIT NO. 6

CIRCUIT _____

OTHER _____, T_{CASE} 35 °C

REF. PIX NOS. _____

$V_{CE} =$ 300 V PEAK, $I_C =$ 60 A PEAK, FREQ 8 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 2-24-T

INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 76.2 WATTS

2. PEAK POWER DISSIPATED 11900 WATTS

3. STORAGE TIME (TO 10% FALL) 4.2 μ S, (I_C) OR V_{CE}

4. FALL TIME (10% TO 90%) 0.7 μ S, (I_C) OR V_{CE}

5. $-dI_C/dt$ _____ A/ μ S

6. $-dI_{B2}/dt$ _____ A/ μ S

7. $-I_{B2}$ _____ A PEAK

8. $-V_{BE}$ _____ V AVERAGE

9. OTHER _____

B. TURN ON, REF. PIX NOS. 2-24-W, WA

INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 7 μ S

1. AVERAGE POWER DISSIPATED 86.4 WATTS

2. PEAK POWER DISSIPATED 12000 WATTS

3. DELAY TIME (TO 10% RISE) 50.1 μ S, (I_C) OR V_{CE}

4. RISE TIME (10% TO 90%) 0.4 μ S, (I_C) OR V_{CE}

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TITLE

NASA EM ACTUATOR
POWER CIRCUIT
DEVICE TESTS (CONTINUED)

PREPARED

DATE

CHECKED

APPROVED

5. dI_C/dt _____ A/ μ s
6. dI_{B1}/dt _____ A/ μ s
7. I_{B1} _____ 9 A AVERAGE, _____ 18 A PEAK
8. V_{BE} _____ V PEAK
9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)

INTERVAL (AFTER LOGIC TURN ON) _____ μ s TO _____ μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR

(OVER INTERVAL ABOVE) _____ 38.4 WATTS

2. AVERAGE POWER DISSIPATED IN BASE

(OVER TOTAL ON INTERVAL) _____ 8.6 WATTS

3. V_{BE} _____ 1.2 V @ I_{B1} _____ 9 A

4. PERCENT ON TIME _____ 80 %

5. V_{CE} _____ .8 V @ I_C _____ 60 A

6. OTHER C. TOTAL 47 W

D. SUMMARY OF LOSSES

1. TURN OFF _____ 76.2 WATTS

2. TURN ON _____ 86.4 WATTS

3. QUASISTATIC ON _____ 47 WATTS

4. TOTAL LOSSES _____ 209.6 WATTS

E. COMMENTS:

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE C11
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <u>PH</u> DATE <u>12-5-77</u> CHECKED _____ APPROVED _____		

D.U.T. TYPE Power Tech PT-4503, UNIT NO. 2

CIRCUIT _____

OTHER _____, T_{CASE} _____ °C

REF. PIX NOS. 3-2-T1, 3-2-T2

$V_{CE} =$ 300 V PEAK, $I_C =$ 59 A PEAK, FREQ 8 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 3-2-T1

INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 147 WATTS
2. PEAK POWER DISSIPATED 10500 WATTS
3. STORAGE TIME (TO 10% FALL) 3.8 μ S, (I_C) OR V_{CE}
4. FALL TIME (10% TO 90%) 3 μ S, (I_C) OR V_{CE}
5. $-dI_C/dt$ _____ A/ μ S
6. $-dI_{B2}/dt$ _____ A/ μ S
7. $-I_{B2}$ _____ A PEAK
8. $-V_{BE}$ _____ V AVERAGE
9. OTHER _____

B. TURN ON, REF. PIX NOS. 3-2-T2

INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 126 WATTS
2. PEAK POWER DISSIPATED 12600 WATTS
3. DELAY TIME (TO 10% RISE) 0.2 μ S, (I_C) OR V_{CE}
4. RISE TIME (10% TO 90%) 0.8 μ S, (I_C) OR V_{CE}

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS	PREPARED <i>G.H. Amato</i> CHECKED APPROVED DATE 2/23/77
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D.U.T. TYPE WEST. 17B-6, UNIT NO. 6

CIRCUIT WITH ANTISATURATION CLAMP ON COLLECTOR

OTHER _____, T_{CASE} < 40 °C

REF. PIX NOS. 2-16-D, E, F, G, H

V_{CE} = 150 V PEAK, I_C = 32 A PEAK, FREQ 4 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 2-16-D

INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 4.8 WATTS
2. PEAK POWER DISSIPATED 2400 WATTS
3. STORAGE TIME (TO 10% FALL) 2.0 μ S, I_C OR V_{CE}
4. FALL TIME (10% TO 90%) 0.5 μ S, I_C OR V_{CE}
5. $-dI_C/dt$ 67 A/ μ S
6. $-dI_{B2}/dt$ 13 A/ μ S
7. $-I_{B2}$ 5 A PEAK
8. $-V_{BE}$ 8.5 V AVERAGE
9. OTHER _____

B. TURN ON, REF. PIX NOS. 2-16-F

INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 7 μ S

1. AVERAGE POWER DISSIPATED 6.4 WATTS
2. PEAK POWER DISSIPATED 3200 WATTS
3. DELAY TIME (TO 10% RISE) 0.1 μ S, I_C OR V_{CE}
4. RISE TIME (10% TO 90%) 0.4 μ S, I_C OR V_{CE}

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	PREPARED <i>G.H. Barndt</i> 2/23/77 CHECKED APPROVED			
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS (CONTINUED)				

5. dI_C/dt 105 A/ μ s
6. dI_{B1}/dt 12 A/ μ s
7. I_{B1} 6 A AVERAGE, 15 A PEAK
8. V_{BE} _____ V PEAK
9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)

INTERVAL (AFTER LOGIC TURN ON) 7 μ s TO 207 μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR
(OVER INTERVAL ABOVE) 44.8 WATTS
2. AVERAGE POWER DISSIPATED IN BASE
(OVER TOTAL ON INTERVAL) 4.8 WATTS
3. V_{BE} 1 V @ I_{B1} 6 A
4. PERCENT ON TIME 80 %
5. V_{CE} 1.75 V @ I_C 32 A
6. OTHER C. TOTAL 49.6

D. SUMMARY OF LOSSES

1. TURN OFF 4.8 WATTS
2. TURN ON 6.4 WATTS
3. QUASISTATIC ON 49.6 WATTS
4. TOTAL LOSSES 60.8 WATTS

E. COMMENTS:

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <u>G. H. Barrett</u> DATE <u>2/23/77</u> CHECKED _____ APPROVED _____		

D.U.T. TYPE WEST 17B-6, UNIT NO. 6
 CIRCUIT WITHOUT CLAMP
 OTHER _____, T_{CASE} < 35 °C
 REF. PIX NOS. 2-16-I, J, K, L, M
 $V_{CE} =$ 150 V PEAK, $I_C =$ 32 A PEAK, FREQ 4 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 2-16-K
 INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 4.2 WATTS
2. PEAK POWER DISSIPATED 2300 WATTS
3. STORAGE TIME (TO 10% FALL) 3.6 μ S, (I_C) OR V_{CE}
4. FALL TIME (10% TO 90%) 0.4 μ S, (I_C) OR V_{CE}
5. $-dI_C/dt$ 105 A/ μ S
6. $-dI_{B2}/dt$ 23 A/ μ S
7. $-I_{B2}$ 5 A PEAK
8. $-V_{BE}$ 8.5 V AVERAGE
9. OTHER _____

B. TURN ON, REF. PIX NOS. 2-16-L
 INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 7 μ S

1. AVERAGE POWER DISSIPATED 6.4 WATTS
2. PEAK POWER DISSIPATED 3200 WATTS
3. DELAY TIME (TO 10% RISE) 0.1 μ S, (I_C) OR V_{CE}
4. RISE TIME (10% TO 90%) 0.4 μ S, (I_C) OR V_{CE}

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS (CONTINUED)		PREPARED <i>G. H. Barrett</i>	DATE 2/23/77	
		CHECKED		
		APPROVED		

5. dI_C/dt 105 A/ μ s
6. dI_{B1}/dt 12 A/ μ s
7. I_{B1} 6 A AVERAGE, 15 A PEAK
8. V_{BE} _____ V PEAK
9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)

INTERVAL (AFTER LOGIC TURN ON) 7 μ s TO 207 μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR

(OVER INTERVAL ABOVE) 6.4 WATTS

2. AVERAGE POWER DISSIPATED IN BASE

(OVER TOTAL ON INTERVAL) 4.8 WATTS

3. V_{BE} 1 V @ I_{B1} 6 A

4. PERCENT ON TIME 80 %

5. V_{CE} .25 V @ I_C 32 A

6. OTHER C. TOTAL 11.2W

D. SUMMARY OF LOSSES

1. TURN OFF 4.2 WATTS

2. TURN ON 6.4 WATTS

3. QUASISTATIC ON 11.2 WATTS

4. TOTAL LOSSES 21.8 WATTS

E. COMMENTS:

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DELCO ELECTRONICS GENERAL MOTORS CORPORATION	REPORT NO.	PAGE	JOB NO. EE-22T-EMA-022	PAGE C16
TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS		PREPARED <i>A.H. Barnett</i> CHECKED DATE 2/23/77 APPROVED		

D.U.T. TYPE WEST. 17B-6, UNIT NO. 6
 CIRCUIT WITHOUT CLAMP
 OTHER _____, T_{CASE} < 40 °C
 REF. PIX NOS. 2-16-N, O, P
 $V_{CE} =$ 200 V PEAK, $I_C =$ 42 A PEAK, FREQ 4 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 2-16-N
 INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 8.8 WATTS
2. PEAK POWER DISSIPATED 4400 WATTS
3. STORAGE TIME (TO 10% FALL) 3.4 μ S, I_C OR V_{CE}
4. FALL TIME (10% TO 90%) 0.5 μ S, I_C OR V_{CE}
5. $-dI_C/dt$ 105 A/ μ S
6. $-dI_{B2}/dt$ 23 A/ μ S
7. $-I_{B2}$ 5 A PEAK
8. $-V_{BE}$ 8.5 V AVERAGE
9. OTHER _____

B. TURN ON, REF. PIX NOS. 2-16-O
 INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 7 μ S

1. AVERAGE POWER DISSIPATED 13 WATTS
2. PEAK POWER DISSIPATED 5400 WATTS
3. DELAY TIME (TO 10% RISE) 0.1 μ S, I_C OR V_{CE}
4. RISE TIME (10% TO 90%) 0.4 μ S, I_C OR V_{CE}

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS (CONTINUED)		PREPARED <i>G. H. Barnett</i> 2/23/77 CHECKED APPROVED		

5. dI_C/dt 125 A/ μ s

6. dI_{B1}/dt 12 A/ μ s

7. I_{B1} 6 A AVERAGE, 15 A PEAK

8. V_{BE} _____ V PEAK

9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)

INTERVAL (AFTER LOGIC TURN ON) 7 μ s TO 207 μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR
 (OVER INTERVAL ABOVE) 6 WATTS

2. AVERAGE POWER DISSIPATED IN BASE
 (OVER TOTAL ON INTERVAL) 4.8 WATTS

3. V_{BE} 1 V @ I_{B1} 6 A

4. PERCENT ON TIME 80 %

5. V_{CE} 25 V @ I_C 30 A

6. OTHER C.TOTAL 10.8W

D. SUMMARY OF LOSSES

1. TURN OFF 8.8 WATTS

2. TURN ON 13 WATTS

3. QUASISTATIC ON 10.8 WATTS

4. TOTAL LOSSES 32.6 WATTS

E. COMMENTS: _____

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS	PREPARED <i>A.H. Bantz</i> CHECKED APPROVED DATE 2/23/77
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D.U.T. TYPE WEST. 178-6, UNIT NO. 6

CIRCUIT WITHOUT CLAMP

OTHER _____, T_{CASE} < 50 °C

REF. PIX NOS. 2-16-Q, R, S, T, V

$V_{CE} =$ 230 V PEAK, $I_C =$ 46 A PEAK, FREQ 4 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 2-16-Q

INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 12 WATTS
2. PEAK POWER DISSIPATED 6000 WATTS
3. STORAGE TIME (TO 10% FALL) 3.6 μ S, I_C OR V_{CE}
4. FALL TIME (10% TO 90%) 0.7 μ S, I_C OR V_{CE}
5. $-dI_C/dt$ 95 A/ μ S
6. $-dI_{B2}/dt$ 23 A/ μ S
7. $-I_{B2}$ 5 A PEAK
8. $-V_{BE}$ 8.5 V AVERAGE
9. OTHER _____

B. TURN ON, REF. PIX NOS. 2-16-S

INTERVAL (AFTER LOGIC TURN ON) 0 μ S TO 7 μ S

1. AVERAGE POWER DISSIPATED 20 WATTS
2. PEAK POWER DISSIPATED 7200 WATTS
3. DELAY TIME (TO 10% RISE) 0.1 μ S, I_C OR V_{CE}
4. RISE TIME (10% TO 90%) 0.4 μ S, I_C OR V_{CE}

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TITLE NASA EM ACTUATOR POWER CIRCUIT DEVICE TESTS (CONTINUED)		PREPARED A. H. Barnett CHECKED	DATE 2/23/77
		APPROVED	

5. dI_{IC}/dt 150 A/ μ s
6. dI_{BI}/dt 12 A/ μ s
7. I_{BI} 9 A AVERAGE, 18 A PEAK
8. V_{BE} 2.5 V PEAK
9. OTHER _____

C. QUASISTATIC ON (STATIC ON INTERVAL)

INTERVAL (AFTER LOGIC TURN ON) 7 μ s TO 207 μ s

1. AVERAGE POWER DISSIPATED IN COLLECTOR
(OVER INTERVAL ABOVE) 14.7 ~~W~~ WATTS
2. AVERAGE POWER DISSIPATED IN BASE
(OVER TOTAL ON INTERVAL) 9 WATTS
3. V_{BE} 1.1 V @ I_{BI} 9 A
4. PERCENT ON TIME 80 %
5. V_{CE} .40 ~~35~~ V @ I_C 46 A
6. OTHER C. TOTAL 23.7 W

D. SUMMARY OF LOSSES

1. TURN OFF 12 WATTS
2. TURN ON 20 WATTS
3. QUASISTATIC ON 23.7 WATTS
4. TOTAL LOSSES 55.7 WATTS

E. COMMENTS: _____

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POWER CIRCUIT
DEVICE TESTS

PREPARED
A. H. Barnett 2-24-77
CHECKED
APPROVED

D.U.T. TYPE WEST. 178-6, UNIT NO. 6

CIRCUIT

OTHER _____, T_{CASE} 85 °C

REF. PIX NOS. _____

V_{CE} = 300 V PEAK, I_C = 60 A PEAK, FREQ 8 KHZ

SUMMARY OF LOSSES AND SWITCHING TIMES

A. TURN OFF, REF. PIX NOS. 2-24-U

INTERVAL (AFTER LOGIC TURN OFF) 0 μ S TO 10 μ S

1. AVERAGE POWER DISSIPATED 110 WATTS

2. PEAK POWER DISSIPATED 11000 WATTS

3. STORAGE TIME (TO 10% FALL) 5.5 μ S, I_C OR V_{CE}

4. FALL TIME (10% TO 90%) 1.5 μ S, I_C OR V_{CE}

5. $-dI_C/dt$ _____ A/ μ S

6. $-dI_{B2}/dt$ _____ A/ μ S

7. $-I_{B2}$ _____ A PEAK

8. $-V_{BE}$ _____ V AVERAGE

9. OTHER _____

B. TURN ON, REF. PIX NOS. _____

INTERVAL (AFTER LOGIC TURN ON) _____ μ S TO _____ μ S

1. AVERAGE POWER DISSIPATED _____ WATTS

2. PEAK POWER DISSIPATED _____ WATTS

3. DELAY TIME (TO 10% RISE) _____ μ S, I_C OR V_{CE}

4. RISE TIME (10% TO 90%) _____ μ S, I_C OR V_{CE}

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ENGINEERING EXHIBIT

APPENDIX D

POWER TRANSISTOR DATA SHEETS

This appendix presents manufacturer's data sheets for some of the candidate power transistors.



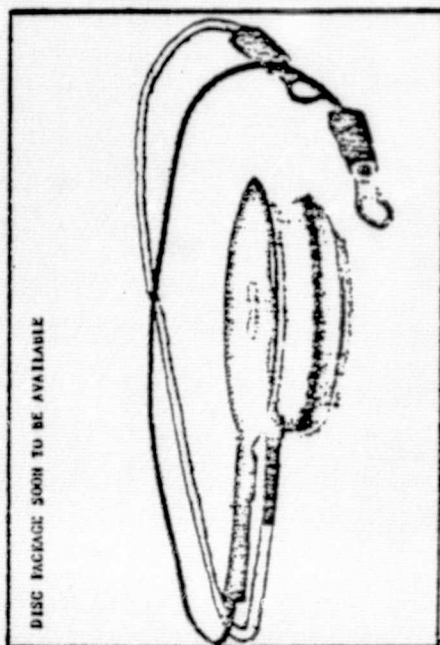
D60T & D62T

NPN SWITCHING POWER TRANSISTOR

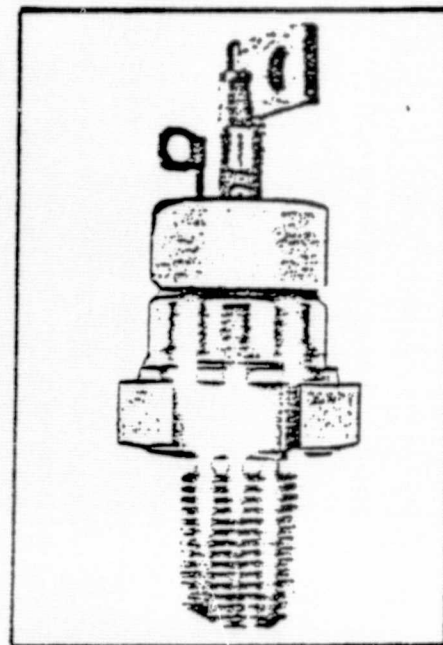
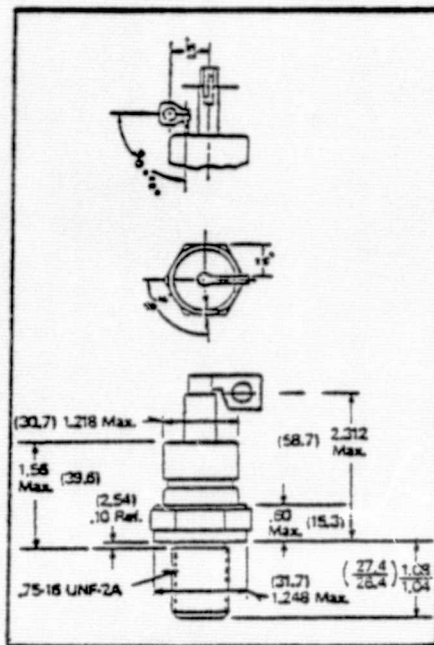
200 AMPS PEAK
50 AMPS GAIN RATING

EE-22T-EMA-022

D1



DISC PACKAGE SOON TO BE AVAILABLE



Maximum Ratings

Collector Current (peak): 200 Amperes
Collector Current (continuous): 100 Amperes
Base Current (continuous): 20 Amperes
Power Dissipation: 625 Watts
at $T_C = 75^\circ\text{C}$
Operating and Storage Temperature: -50°C to $+200^\circ\text{C}$

Applications

- High Frequency Inverters
- Motor Controls
- Switching Regulators
- VLF Transmitters

Features

- Triple Diffused Design
- CBE Construction (No Solder Joints)
- 625 Watt Power Capability

Ordering Information - Obtain optimum device performance for your application by selecting proper order code.

Type	Voltage		Current		Gain	
Code	V_{CE0} (SUS)	V_{CE0}	Code	I_{DC}	Code	Code
D60T	400	400	40	40	40	10
(Stud)	450	450	45	50	50	10
D62T	500	500	50	60	60	10
(Disc)						

Example

Obtain optimum device performance for your application by selecting proper Order Code.

Type	Voltage		Current		Gain
D 6 0 T	4	0	5	0	10

The above number describes a stud mount transistor rated at 400 volts, with a gain of 10 at 50 amperes.

NEW PRODUCT

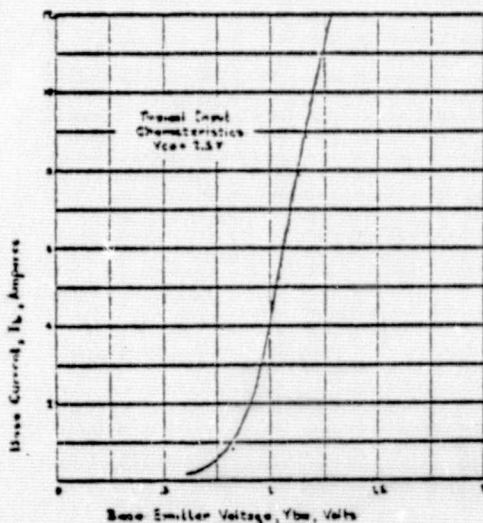
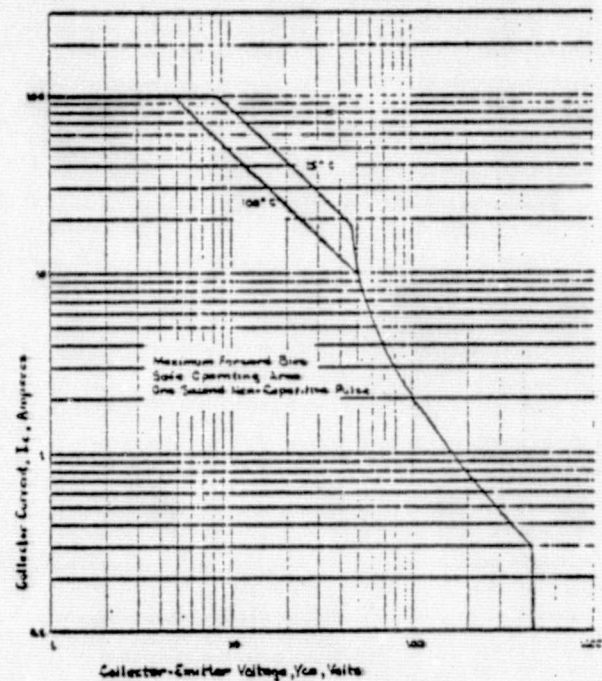
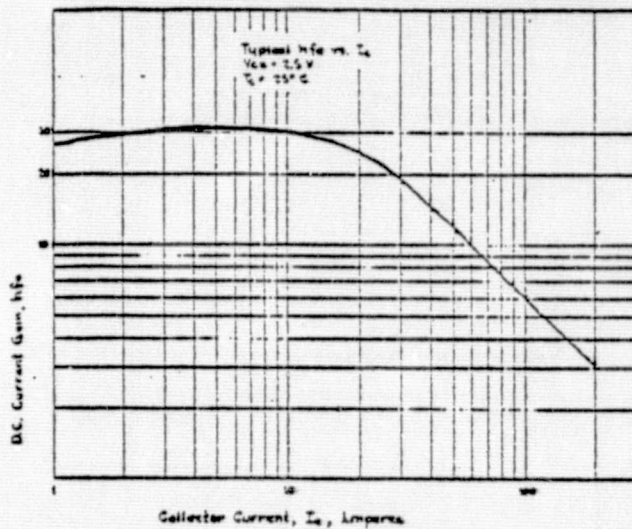
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PRELIMINARY DATA OCTOBER 1977

POWER TRANSISTOR

Electrical Characteristics* (T_{case} = 25°C unless otherwise specified)

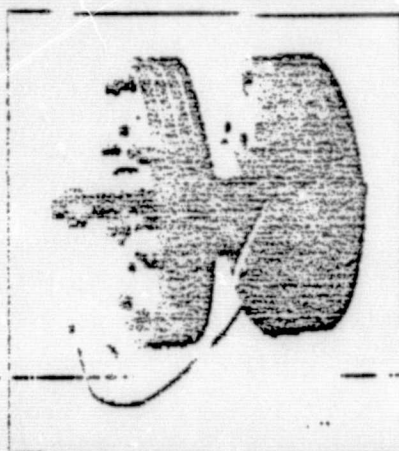
SYMBOL	CHARACTERISTIC	TEST CONDITIONS	MIN	TYP	MAX	UNITS
V _{CE0} (SUS)	Collector-Emitter Sustaining Voltage	I _C = 200mA I _B = 0 100μs Pulse	See Page 1			
I _{CEV}	Collector Cutoff Current (Base-Emitter Reverse Biased)	At Rated V _{CE0} V _{BE} (OFF) = -1.5V		10	100	μA
I _{CEV}	Collector Cutoff Current (Base-Emitter Reverse Biased)	At Rated V _{CE} V _{BE} (OFF) = -1.5V, T _C = 150°C		.8	3	mA
I _{CEO}	Emitter Cutoff Current	V _{EB} = 7V			1	mA
h _{FE}	DC Current Gain	I _C = 10A, V _{CE} = 2.5V	10	15		
h _{FE}	DC Current Gain	I _C = 10A, V _{CE} = 2.5V		5		
V _{CE} (SAT)	Collector-Emitter Saturation Voltage	I _C = 10A, I _B = 4A		.75	1.25	Volts
V _{BE} (SAT)	Base-Emitter Saturation Voltage	I _C = 10A, I _B = 4A		1.0	1.5	Volts
C _{OB}	Output Capacitance	f _{TEST} = 1 MHz, V _{CE} = 10V		2500		μs
f _T	Gain-Bandwidth Product	f _{TEST} = 1 MHz, I _C = 1A, V _{CE} = 10V	7	10		MHz
R _{θJC}	Thermal Resistance Junction to Case	V _{CE} = 10V			0.2	°C/W
t _g	Turn-On Delay	V _{CE} = 100V, I _C = 10A I _{B1} = I _{B2} = 4A, t _p = 100μs Duty Cycle <2%			100	ns
t _r	Rise Time				0.5	μs
t _s	Storage Time				2.5	μs
t _f	Fall Time				0.5	μs



D60T & D62T

NPN SWITCHING
POWER TRANSISTOR200 AMPS PEAK
50 AMPS GAIN RATINGPreliminary Technical Data

These devices are developmental types intended for engineering evaluation. Specifications and data are subject to change without prior notice. Vestinghouse assumes no obligation for notice of change or future manufacture of these products.



High-Current NPN Transcalent Power Transistor

100 Amperes Pulse Collector Current Rating
750 Volts Collector Voltage Breakover Rating

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- Integral Heat Exchanger
- Lower Junction Temperature
- Large Safe Operating Area
- Simplified Replacement
- Forced-Air-Cooled
- Light Weight
- Emitter Ballasted
- Optimized Thermal Interfaces

The RCA Dev. No. J15492 is a forced-air-cooled, silicon power transistor for high-current, high voltage military applications. New heat dissipation techniques are used to reduce the thermal impedance of the transistor, thereby lowering the junction temperature. A heat pipe is directly bonded to the transistor water to enhance heat flow between the water and the integral cooling fins. Field replacement is simplified by the elimination of the need for separate clamped or threaded heat sinks. The reduced thermal impedance of the J15492 results in an increased current and dissipation capability as compared with conventional devices.

The J15492 can be useful in a variety of applications, such as solid-state switches, motor controllers and suppressors, voltage regulators and power conditioning equipment. The size and weight of the J15492 when related to its rated current, make it well suited for airborne, marine and portable mobile equipment where compactness, light weight and high reliability are prime considerations.

The silicon water utilized in the J15492 features a multiplicity of parallel emitter elements. Integral emitter ballast resistors assure proportional current sharing and a large safe operating area. Operation with both high current and high voltage is thus enhanced.

Characteristic Ranges

Collector-Base Voltage	V _{CB0}	(max.) 750	V
Collector-To-Emitter Sustaining Voltage With -1.0 V Reverse Bias (V _{RE})	V _{CEX}	(typ.) 750	V
Collector-To-Emitter Sustaining Voltage	V _{CE0} (150%)	(typ.) 500 (min.) 400	V
Collector-To-Emitter Saturation Voltage at I _C = 50 A	V _{CE(SAT)}	(typ.) 0.90 (max.) 1.25	V
Emitter-To-Base Voltage	V _{EB0}	(max.) 10	V
Collector Current (Continuous at I _{BE} = 10)	I _C	(typ.) 50	A
Collector Current (Peak pulse) at I _{BE} = 0	I _C	(typ.) 100	A
Current Gain (Continuous)	h _{FE}	5 to 40	
Base Current (Continuous)	I _B	(max.) 10	A
Base Current (Peak pulse)	I _B	(max.) 18	A
Average Dissipation at T _{amb} = 250°C	P _D	(max.)	
With natural convection cooling*		150	W
With 510 LPM forced air (7-50 cfm)		400	W
With 2100 LPM forced air (14-300 cfm)		500	W
Temperature Ranges			
Junction operating	T _J	25 to 200	°C
Case operating (Base of fin)	T _C	0 to 110	°C
Storage	T _S	-55 to 200	°C
Cut Off Frequency	f _{cut}	(min.) 4	KHz
Turn-On Time			
Delay time	t _d	(typ.) 0.22	μsec
Rise time	t _r	(typ.) 0.11	μsec

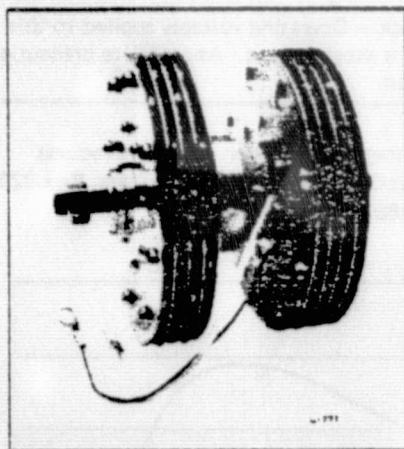
- * Pulse duration = 300 μsec. Duty cycle ≤ 2%. Greatest pulse dissipation occurs during Turn-on and Turn-off but the averaged values may permit natural convection cooling in some applications.
- † The air flow requirements are based on laboratory conditions at sea level and 25°C and are limiting conditions. Compensation is necessary for operation at altitude or in higher ambient air temperatures. See AN 4859 "Application Guide for Forced-Air Cooling".

For further information or application assistance on this device, contact your RCA Sales Representative or write RCA, Dept. EE-22T, P.O. Box 100, Hickory, NC 28604.

This drawing is a preliminary drawing and is subject to change without notice. The user is advised that this drawing is not to be used for manufacturing purposes without the approval of RCA.

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Transcalent Device
Developmental Type
J15492



High-Current NPN Transcendent Power Transistor

100 Amperes Pulse Collector Current Rating
750 Volts Collector Voltage Breakover Rating

- Integral Heat Exchanger
- Lower Junction Temperature
- Large Safe Operating Area
- Simplified Replacement
- Forced-Air-Cooled
- Light Weight
- Emitter Ballasted
- Optimized Thermal Interfaces

The RCA P95200EE4 is a forced-air-cooled, silicon-power transistor for high current, high voltage military and industrial applications. New heat dissipation techniques are used to reduce the thermal impedance of the transistor, thereby lowering the junction temperature. A heat pipe is directly bonded to the transistor wafer to enhance heat flow between the wafer and the integral cooling fins. Field replacement is simplified by the elimination of the need for separate clamped or threaded heat sinks. The reduced thermal impedance results in an increased current and dissipation capability as compared with conventional devices.

The P95200EE4 can be useful in a variety of applications, such as solid-state switches, motor controllers, arc suppressors, voltage regulators and power conditioning equipment. The size and weight of the P95200EE4 when related to its rated current, make it well suited for airborne, marine and portable/mobile equipment where compactness, light weight and high reliability are prime considerations.

The silicon wafer utilized in the P95200EE4 features a multiplicity of paralleled emitter elements. Integral emitter ballast resistors assure proportional current sharing and a large safe operating area. Operation with both high current and high voltage is thus enhanced.

Characteristic Ranges

Collector-To-Base Voltage ...	V_{CB0}	(max.) 750	V
Collector-To-Emitter Sustaining Voltage With -1.5 V Reverse Bias (V_{BE})	V_{CEX}	(typ.) 750	V
Collector-To-Emitter Sustaining Voltage	$V_{CE0(SUS)}$	(typ.) 500 (min.) 400	V
Collector-To-Emitter Saturation Voltage at $I_C = 60$ A	$V_{CE(SAT)}$	(typ.) 0.90 (max.) 1.25	V
Emitter-To-Base Voltage ...	V_{EB0}	(max.) 10	V
Collector Current (Continuous) at $h_{FE} = 10$	I_C	(typ.) 60	A
Collector Current (Peak pulse) ^a at $h_{FE} = 6$	I_C	(typ.) 100	A
Current Gain (Continuous)	h_{FE}	5 to 40	
Base Current (Continuous)	I_B	(max.) 10	A
Base Current (Peak pulse) ^a	I_B	(max.) 18	A
Average Dissipation ^b at $T_{amb} = 25^\circ$ C:	P_D	(max.)	
With natural convection cooling ^a		150	W
With 510 LFM forced air (≈ 50 cfm)		400	W
With 3000 LFM forced air (≈ 300 cfm)		500	W
Temperature Ranges:			
Junction, operating	T_J	-25 to 200	$^\circ$ C
Case, operating (Base of fins)	T_C	0 to 110	$^\circ$ C
Storage	T_S	-55 to 175	$^\circ$ C
Cut-Off Frequency	f_{hfe}	(min.) 4	KHz
Turn-On Time:			
Delay time	t_d	(typ.) 0.22	μ sec
Rise time	t_r	(typ.) 0.3	μ sec

^a Pulse duration = 300 μ sec. Duty cycle $\leq 2\%$. Greatest pulse dissipation occurs during Turn-on and Turn-off but the averaged values may permit natural convection cooling in some applications.

^b The air flow requirements are based on laboratory conditions at sea level and 25° C and are limiting conditions. Compensation is necessary for operation at altitude or in higher ambient air temperatures. See AN-4869 "Application Guide for Forced-Air Cooling".

For further information or application assistance on this device, contact your RCA Sales Representative or write Power Marketing, RCA, Lancaster, PA 17604.

This product is in limited pilot commercial production. Minor changes may occur in specification limits as the product data base develops. The warranty is as published. Confirm delivery, specifications and permanent product numbering with RCA prior to placing large-quantity orders, or developing permanent Bills of Materials, specifications, instruction and maintenance booklets, etc.

Information furnished by RCA is believed to be accurate and reliable. However, no responsibility is assumed by RCA for its use; nor for any infringements of patent or other rights of third parties which may result from its use. No license is granted by implication or otherwise under any patent or patent rights of RCA.

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Supersedes J15492 9-76
Printed in U.S.A./8-77
P95200EE4

Turn-Off Time:

Storage time t_s (typ.) 2.0 μsec Fall time t_f (typ.) 0.8 μsec Thermal Resistance: $R_{\theta JC}$

With natural convection cooling

(Case is defined as base of fins) (typ.) 0.2 $^{\circ}\text{C/W}$ With 510 LFM forced air (typ.) 0.4 $^{\circ}\text{C/W}$

Weight 30 oz

Altitude^b (max.) 50,000 ft

Although sturdy, these devices can be damaged if the nuts fastening the leads to the unit are torqued through the body of the device. The stud should be held stationary with an "Allen" wrench while tightening the nut.

Warning — Personal Safety Precautions

Electrical Shock — Operating voltages applied to this device present a shock hazard. Appropriate precautions should be taken.

For further information on Silicon Rectifiers request Technical Booklet SC16 from RCA Solid State, Box 3200, Somerville, NJ 08876.

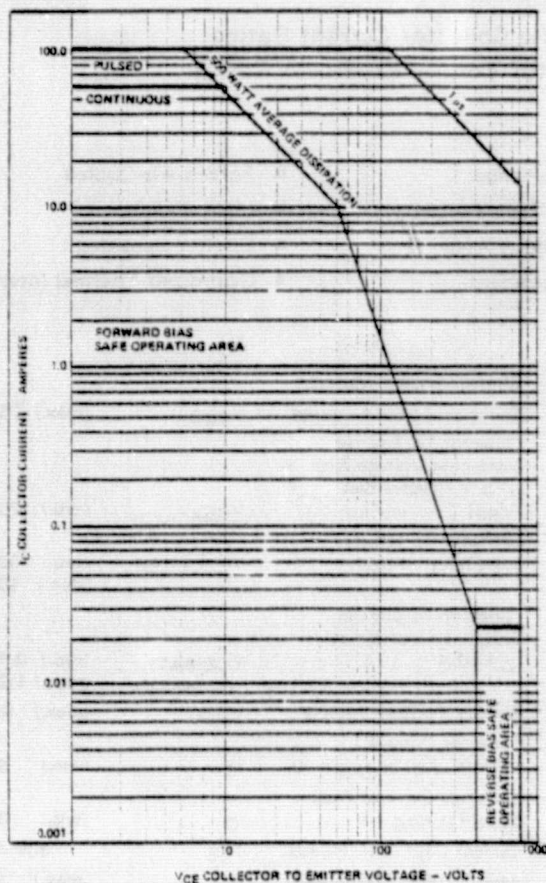
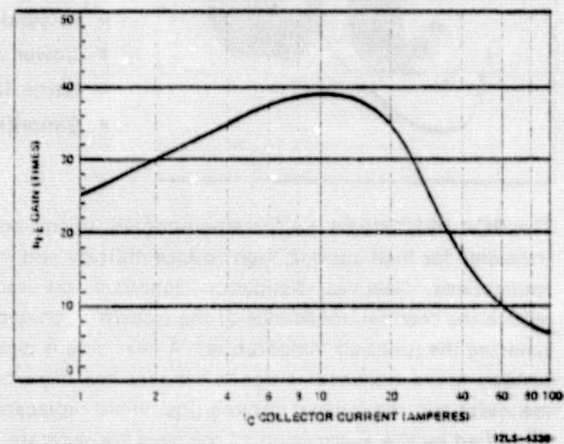
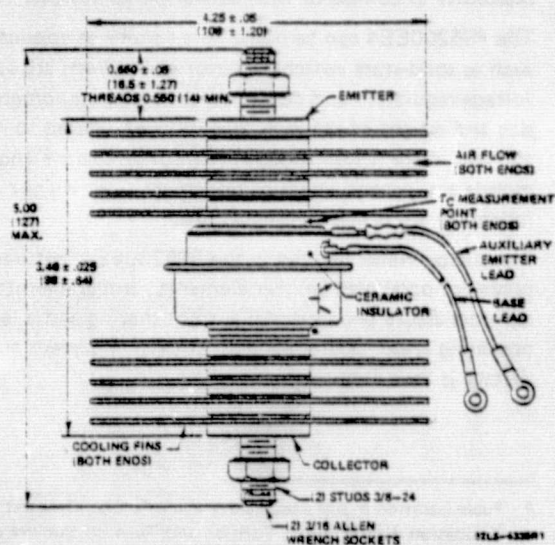


Figure 1 — Safe Operating Area (Objective)

Operating Considerations

Mounting

An air duct of insulating material conforming closely to the cross section of the cooling fins should be used to direct the cooling air through the fins. Mount the P95200EE4 at the output of this duct with one end secured to a fixed bulk-head, bus-bar plate. The other end should be connected by a flexible lead and lug or adjustable insulated terminal adequate for the rated current. The face of the lug is fastened against the end of the heat pipe. The stud should not be used to carry current.

Figure 2 — Typical Gain at $V_{CE} = 5\text{ V}$ 

*Dimensions are in inches unless otherwise stated. Dimensions in parentheses are in millimeters and are derived from the basic inch dimension (1 inch = 25.4 mm).

Figure 3 — Outline

P95200EE4

Turn-Off Time:

Storage time t_s (typ.) 2.0 μsec Fall time t_f (typ.) 0.8 μsec Thermal Resistance: $R_{\theta JC}$ With natural convection cooling
(Case is defined as base of fins) (typ.) 0.2 $^{\circ}\text{C/W}$ With 510 LFM forced air (typ.) 0.4 $^{\circ}\text{C/W}$

Weight 30 oz

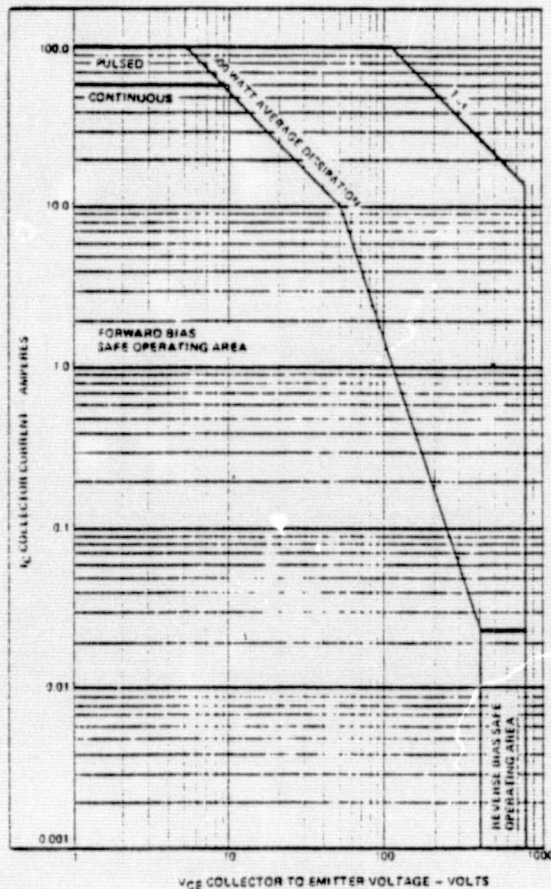
Altitude^b (max.) 50,000 ft

Figure 1 — Safe Operating Area (Objective)

Operating Considerations

Mounting

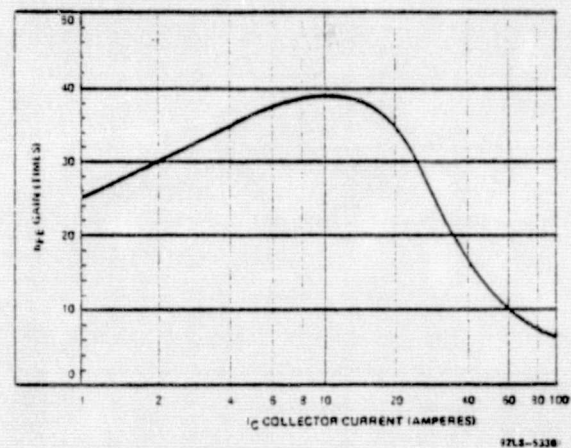
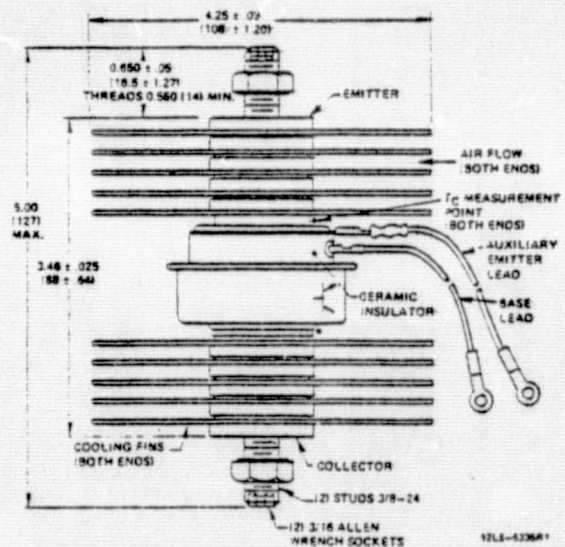
An air duct of insulating material conforming closely to the cross section of the cooling fins should be used to direct the cooling air through the fins. Mount the P95200EE4 at the output of this duct with one end secured to a fixed bulk-head, bus-bar plate. The other end should be connected by a flexible lead and lug or adjustable insulated terminal adequate for the rated current. The face of the lug is fastened against the end of the heat pipe. The stud should not be used to carry current.

Although sturdy, these devices can be damaged if the nuts fastening the leads to the unit are torqued through the body of the device. The stud should be held stationary with an "Allen" wrench while tightening the nut.

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Figure 2 — Typical Gain at $V_{CE} = 5 \text{ V}$ 

*Dimensions are in inches unless otherwise stated. Dimensions in parentheses are in millimeters and are derived from the basic inch dimension (1 inch = 25.4 mm).

Figure 3 — Outline

PowerTech

110 AMPERES

PT-4502

PT-4503 —

HIGH VOLTAGE SILICON NPN TRANSISTOR

ABSOLUTE MAXIMUM RATINGS

	TYPE PT-4502	PT-4503
Collector-Base Voltage, V_{CBO}	400V	450V
Collector-Emitter Voltage, V_{CEO}	325V	400V
Emitter-Base Voltage, V_{EBO}		10V
Peak Collector Current, I_{CM} *		110A
D.C. Collector Current, I_C		60A
Power Dissipation 25°C Case Temperature, P_D		350W
Power Dissipation at 100°C Case Temperature, P_D		200W
Operating Junction Temperature Range, T_J		-65 to 200°C
Storage Temperature Range, T_A		-65 to 200°C
Package:		TQ-114
Thermal Resistance θ_{JC}		0.5°C/W

ELECTRICAL SPECIFICATIONS (at 25°C unless otherwise noted)

TEST	SYMBOL	LIMITS				UNIT	TEST CONDITIONS
		PT-4502		PT-4503			
		MIN.	MAX.	MIN.	MAX.		
D.C. Current Gain*	h_{FE}	10		10			$I_C=60A, V_{CE}=5V$
D.C. Current Gain*	h_{FE}	5		5			$I_C=110A, V_{CE}=5V$
Collector Saturation Voltage*	$V_{CE(sat)}$		0.75		0.75	V	$I_C=60A, I_B=6A$
Base Emitter Voltage*	V_{BE}		1.75		1.75	V	$I_C=60A, V_{CE}=5V$
Col-Em. Breakdown Voltage*	$V_{CEO(sus)}$	325		400		V	$I_C=200mA, I_B=0$
Collector Cutoff Current	I_{CBO}		2	—	—	mA	$V_{CB}=400V, I_{EB}=0$
Collector Cutoff Current	I_{CBO}	—	—		2	mA	$V_{CB}=450V, I_{EB}=0$
Col. Cutoff Current @ 150°C	I_{CBO}		20		20	mA	$V_{CB}=250V, I_{EB}=0$
Emitter Cutoff Current	I_{EBO}		5		5	mA	$V_{EB}=10V, I_{CB}=0$
Gain Bandwidth Product (Typ.)	f_t	10		10		MHz	$I_C=5A, V_{CE}=10V$
Collector Capacitance	C_{obo}		400		400	pf.	$V_{CB}=10V, f=1\text{ MHz}$
Switching Speed (Typ.)	t_r		.5		.5	μs	$I_C=30A, V_{CC}=150V$
	t_s		1.2		1.2	μs	$I_{B1}=I_{B2}=3A$
	t_f		.5		.5	μs	

* $PW \leq 300 \mu s, D.C. \leq 2\%$

ELECTRICAL SPECIFICATIONS (at 25°C unless otherwise noted)

TEST	SYMBOL	PT-3522		PT-3523		UNIT	TEST CONDITIONS
		MIN.	MAX.	MIN.	MAX.		
D.C. Current Gain*	h_{FE}	10	50	10	50	—	$I_C=50A, V_{CE}=5V$
D.C. Current Gain*	h_{FE}	5	—	5	—	—	$I_C=30A, V_{CE}=5V$
Collector Saturation Voltage*	$V_{CE(sat)}$	—	0.6	—	0.6	V	$I_C=50A, I_B=5A$
Base Emitter Voltage*	V_{BE}	—	1.5	—	1.5	V	$I_C=50A, V_{CE}=5V$
Col. -Em. Breakdown Voltage*0	$V_{CEO(sus)}$	325	—	—	—	V	$I_C=50mA, I_B=0$
Col. -Em. Breakdown Voltage*0	$V_{CEO(sus)}$	—	—	400	—	V	$I_C=50mA, I_B=0$
Collector Cutoff Current	I_{CBO}	—	2	—	—	mA	$V_{CB}=400V, I_{EB}=0$
Collector Cutoff Current	I_{CBO}	—	—	—	2	mA	$V_{CB}=450V, I_{EB}=0$
Col. Cutoff Current @ 150°C	I_{CBO}	—	20	—	—	mA	$V_{CB}=250V, I_{EB}=0$
Emitter Cutoff Current	I_{EBO}	—	5	—	5	mA	$V_{EB}=10V, I_{CB}=0$
Gain Bandwidth Product (Typ.)	f_t	10	—	10	—	MHz	$I_C=5A, V_{CE}=10V$
Collector Capacitance	C_{obo}	—	400	—	400	pf.	$V_{CB}=150V, f=100KHz$
Switching Speed (Typ.)	t_r	—	.5	—	.5	μs	$I_C=30A, V_{CC}=150V$
	t_s	—	1.2	—	1.2	μs	$I_{B1} = -I_{B2} = 3A$
	t_f	—	.5	—	.5	μs	

*PW ≤ 300 μs, D.C. ≤ 2%

0 V_{CE} measured with pulse 300 μs max., $I_B=100μA$

Do Not Use Curve Tracer

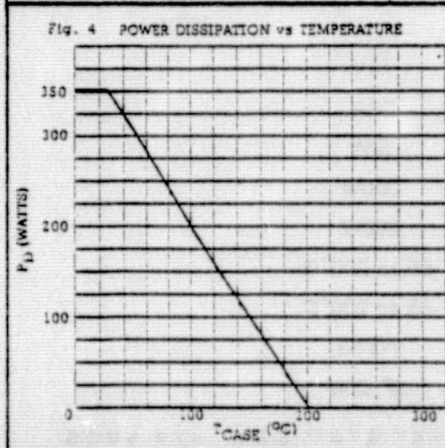
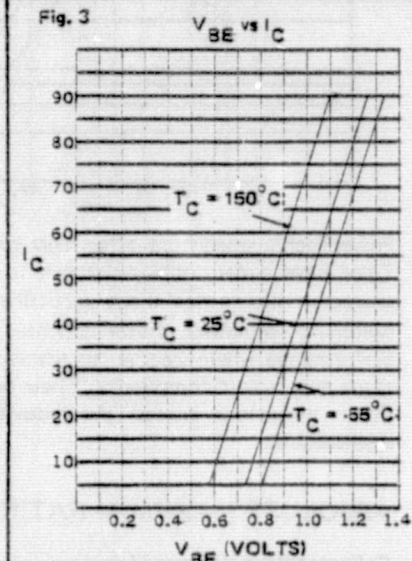
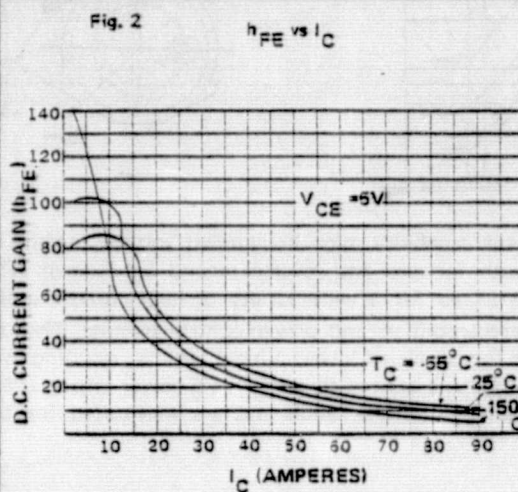
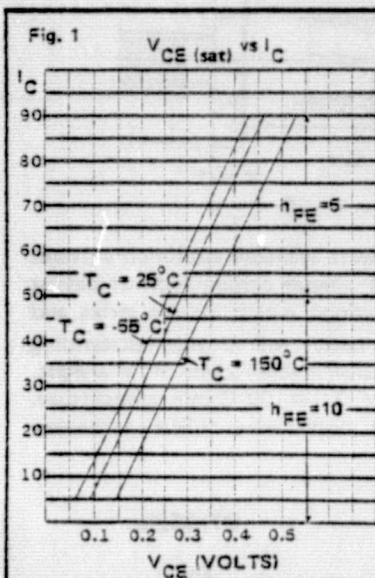
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Fig. 5 SWITCHING TEST CIRCUIT

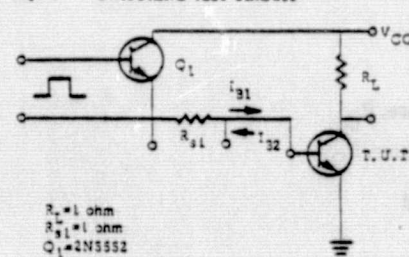
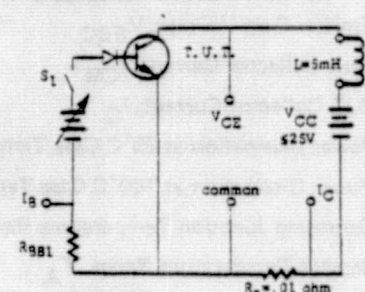


Fig. 6 UNCLAMPED INDUCTIVE SWEEP TEST



PROCEDURE
With S_1 closed, $I_C=35A$
Open S_1
 $E_{S/b} = 1/2LI^2 = 2.5 \text{ joules}$

"BIG IDEAS IN
BIG POWER"

PowerTech

90 AMPERES

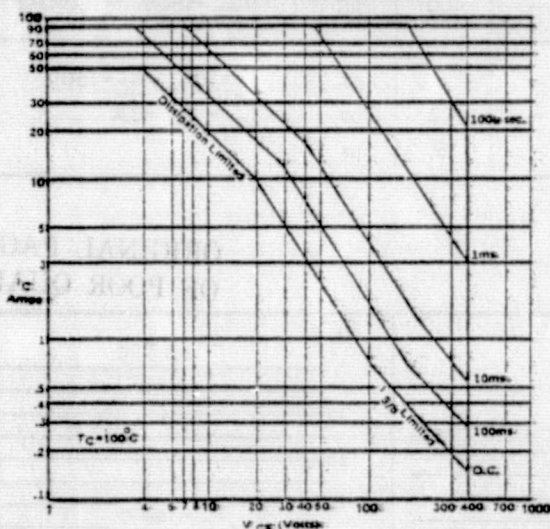
PT-3522
PT-3523

HIGH VOLTAGE SILICON NPN TRANSISTOR

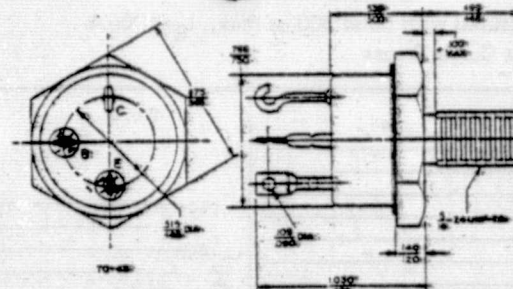
FEATURES

$V_{CE(sat)}$ 0.6V @ 50A h_{FE} 5 min. @ 90A $I_{S/b}$ 1.5A @ 400V
 V_{BE} 1.5V @ 50A t_f 0.5 μ sec. $E_{S/b}$ 2.5 Joules

SAFE OPERATING AREA



JEDEC TO-63



PowerTech's transistors offer high current capability, high breakdown voltage and the lowest available saturation voltage. They have exceptional resistance to both forward and reverse second breakdown. This unique combination of device characteristics makes them particularly suited for a wide variety of high current applications, which include series and switching regulators, motor controls, servoamplifiers and power control circuits. The transistors will provide outstanding performance when used as replacements for paralleled lower current devices, resulting in considerable reductions in weight, space and circuit complexity. Their reliability is assured through 100% power testing at 50V, 2A @ 100°C case temperature. These transistors exceed the requirements of MIL-S-19500 and are well-suited for the most severe military-aerospace applications.

ABSOLUTE MAXIMUM RATINGS

	TYPE PT-3522	PT-3523
Collector-Base Voltage, V_{CBO}	400V	450V
Collector-Emitter Voltage, V_{CEO}	325V	400V
Emitter-Base Voltage, V_{EBQ}		10V
Peak Collector Current, I_{CM}^*		90A
D.C. Collector Current, I_C		50A
Power Dissipation at 25°C Case Temperature, P_D		350W
Power Dissipation at 100°C Case Temperature, P_D		200W
Operating Junction Temperature Range, T_J		-65 to 200°C
Storage Temperature Range, T_A		-65 to 200°C
Package:		TO-63
Thermal Resistance θ_{JC}		.5° C/W

Delco Electronics SEMICONDUCTORS

NPN SILICON

GENERAL DESCRIPTION

The Delco DTS-4066, DTS-4067, DTS-4074 and DTS-4075 are NPN triple diffused silicon Darlington power transistors. Built-in resistors are connected between the bases and emitters for parameter stability. A speedup diode is connected as shown in figure 5 to improve the switching characteristics of the DTS-4074 and DTS-4075.

The case is hermetically sealed and electrically connected to the collector.

Physical dimensions conform to the standard JEDEC TO-3 outline.



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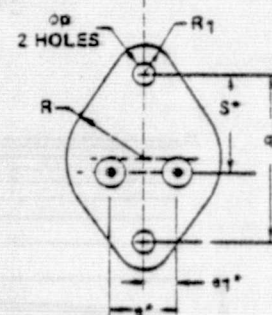
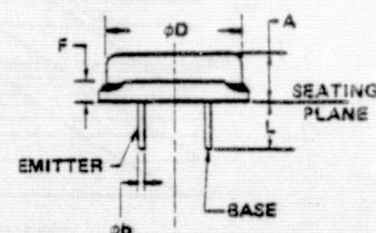
ABSOLUTE MAXIMUM RATINGS

Collector-emitter voltage (V_{CEO})	600V
Collector current, peak (I_C)	25A
Collector current, continuous (I_C)	20A
Base current, continuous (I_B)	5A
Maximum power dissipation	100W
Maximum operating junction temperature	150°C
Minimum operating junction temperature	-65°C
Maximum storage temperature	150°C
Lead temperature 1/16" $\pm$ 1/32" from case for 10 seconds	300°C

ELECTRICAL CHARACTERISTICS

SYM.	PARAMETER	TYPE	CONDITIONS	MIN.	MAX.	UNITS
$V_{(BR)}$ EBO	Emitter-base breakdown voltage	DTS-4066 DTS-4067 DTS-4074 DTS-4075	$I_{EBO} = 50\text{mA}$	7		V
I_{CEO}	Collector cutoff current	All	$V_{CE} = 600\text{V}$		0.25	mA
h_{FE}	Current gain	DTS-4066 DTS-4074 DTS-4067 DTS-4075	$V_{CE} = 5\text{V}, I_C = 10\text{A}$ $V_{CE} = 5\text{V}, I_C = 25\text{A}$ $V_{CE} = 5\text{V}, I_C = 10\text{A}$ $V_{CE} = 5\text{V}, I_C = 25\text{A}$	75 5 150 10		
V_{CE} (sat)	Collector-emitter saturation voltage	DTS-4066 DTS-4074 DTS-4067 DTS-4075	$I_C = 10\text{A}, I_B = 0.5\text{A}$ $I_C = 20\text{A}, I_B = 2.5\text{A}$ $I_C = 10\text{A}, I_B = 0.5\text{A}$ $I_C = 20\text{A}, I_B = 2.5\text{A}$		2.0 3.5 1.5 2.0	V
V_{BE}	Base-emitter saturation voltage	All	$I_C = 10\text{A}, I_B = 0.5\text{A}$		2.3	V
V_{CEO} (sus)	Sustaining voltage	All	$I_C = 2.5\text{A}$ (read at 1.0A) $L = 10\text{mH}$	350		V
$ h_{fe} $	Small signal, short circuit forward current transfer ratio	All	$V_{CB} = 10\text{V}, I_C = 200\text{mA}$ $f = 1\text{MHz}$	8		
C_{obo}	Output capacitance	All	$V_{CB} = 10\text{V}, I_E = 0$ $f = 1\text{MHz}$		200	pf

**DIMENSIONS AND
CONNECTIONS**



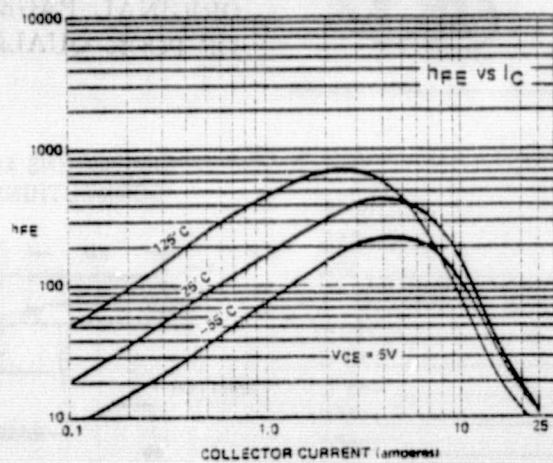
* MEASURED AT SEATING PLANE

SYM	INCHES		MILLIMETERS	
	MIN.	MAX.	MIN.	MAX.
A	.250	.328	6.35	8.33
ϕb	.038	.043	.966	1.092
ϕD		.875		22.22
e	.420	.440	10.67	11.17
e_1	.205	.225	5.21	5.71
F	.060	.135	1.53	3.42
L	.410	.470	10.41	11.94
ϕp	.151	.161	3.84	4.08
q	1.177	1.197	29.90	30.40
R	.495	.525	12.58	13.33
R_1	.131	.188	3.33	4.77
S	.855	.875	16.64	17.14

Delco Electronics SEMICONDUCTORS

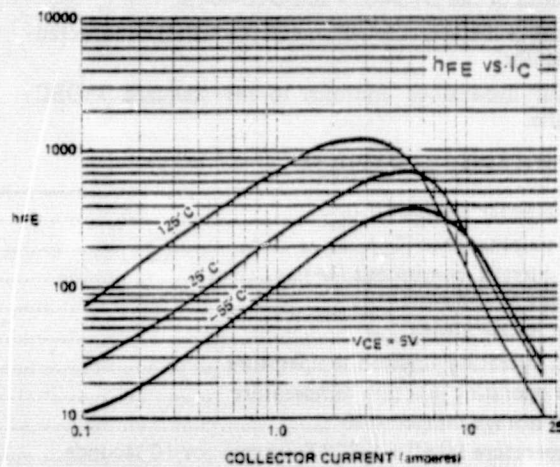
THERMAL CHARACTERISTICS

Thermal resistance, junction to heat sink.....0.75°C/W max.



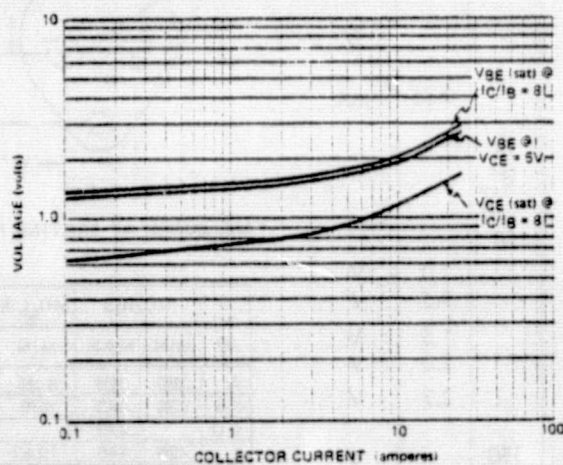
DTS-4066/4074

FIGURE 1



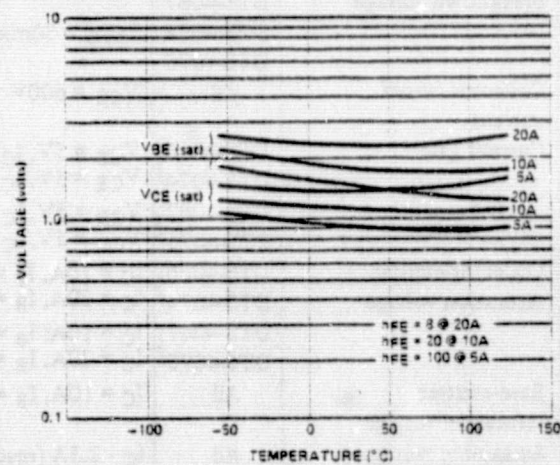
DTS-4067/4075

FIGURE 2



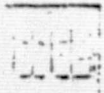
ON VOLTAGE vs COLLECTOR CURRENT

FIGURE 3



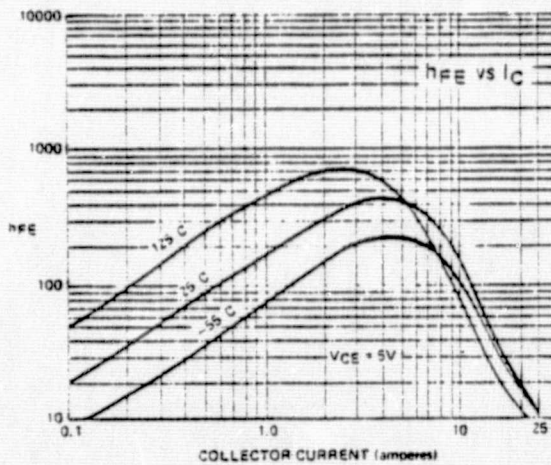
ON VOLTAGE vs TEMPERATURE

FIGURE 4


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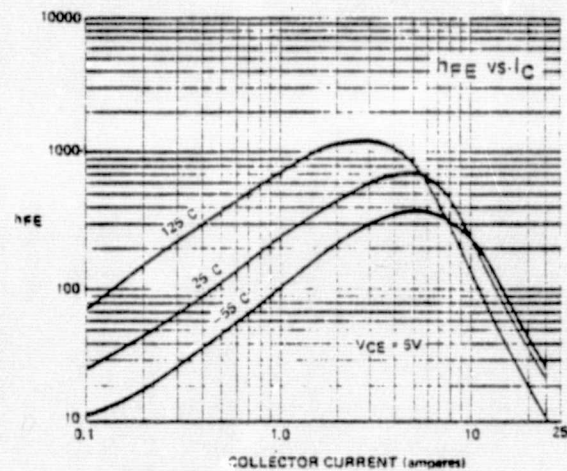
THERMAL CHARACTERISTICS

Thermal resistance, junction to heat sink.....0.75°C/W max.



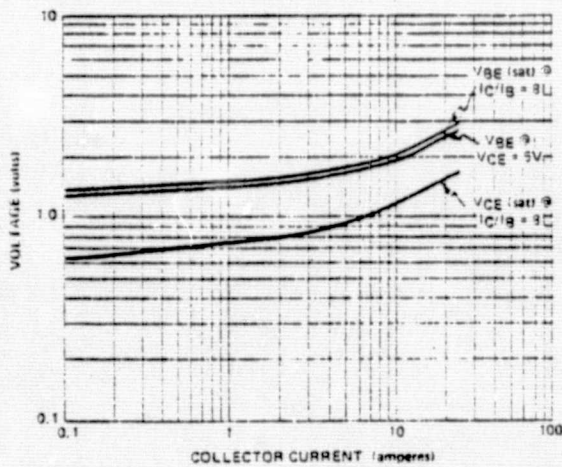
DTS-4066/4074

FIGURE 1



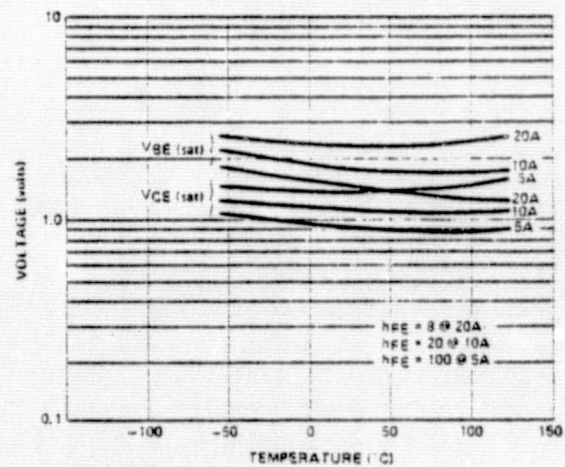
DTS-4067/4075

FIGURE 2



ON VOLTAGE vs COLLECTOR CURRENT

FIGURE 3



ON VOLTAGE vs TEMPERATURE

FIGURE 4

ENGINEERING DATA SHEET

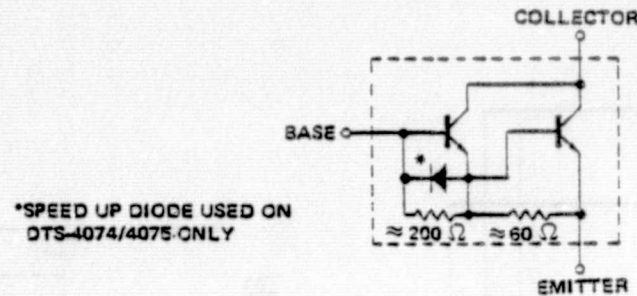


FIGURE 5
DARLINGTON SCHEMATIC

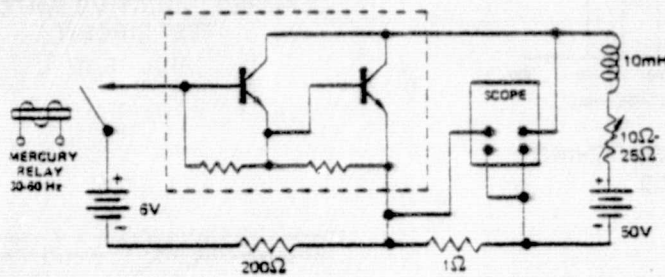


FIGURE 6
 $V_{CE(sus)}$ TEST CIRCUIT

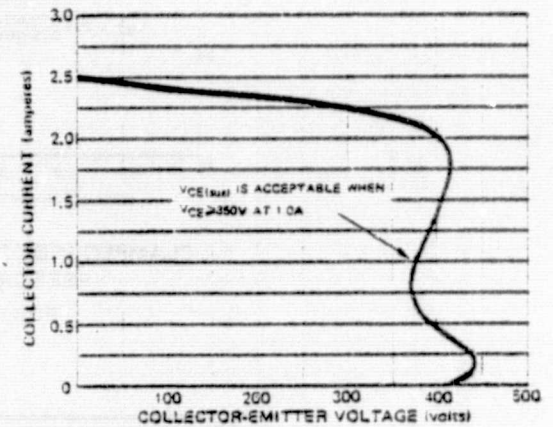


FIGURE 7
 $V_{CE(sus)}$ OSCILLOSCOPE DISPLAY

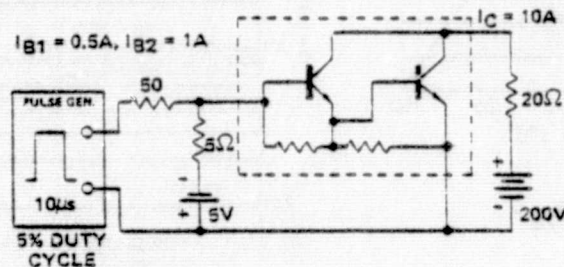


FIGURE 8
COMMON EMITTER SWITCHING TIME
TEST CIRCUIT

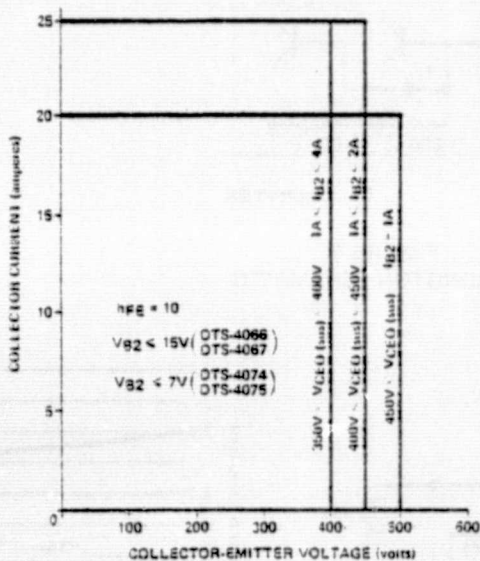
COMMON EMITTER SWITCHING TIME
TEST CIRCUIT

Typical Switching Times:	DTS-4066 DTS-4067	DTS-4074 DTS-4075
Rise time.....	0.5μs	0.5μs
Storage time.....	5.0μs	3.2μs
Fall time.....	4.5μs	1.0μs

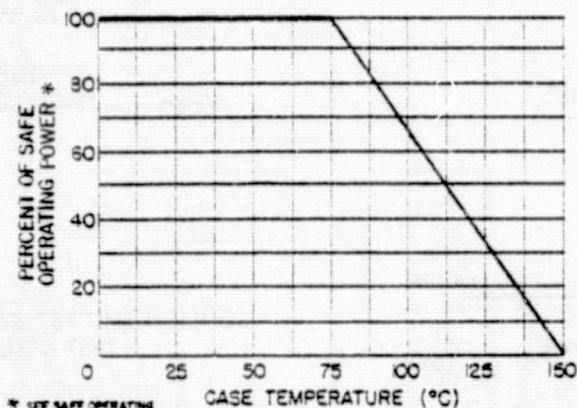
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DTS-4066
DTS-4067
DTS-4074
DTS-4075

Delco Electronics SEMICONDUCTORS



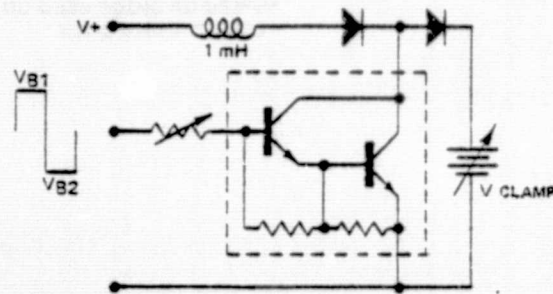
CLAMPED INDUCTIVE SWITCHING
PERFORMANCE
FIGURE 9



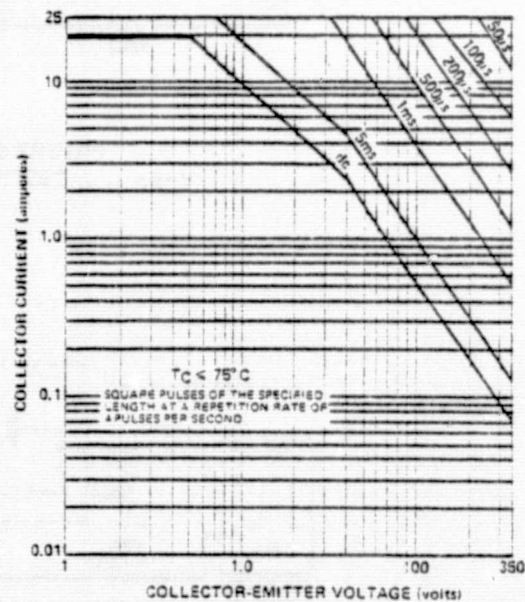
* SEE SAFE OPERATING
CURVES FOR 75°C MAXIMUM
POWER RATINGS AS A FUNCTION OF
COLLECTOR-EMITTER VOLTAGE.

DERATING CURVE

FIGURE 11



CLAMPED INDUCTIVE SWITCHING
TEST CIRCUIT
FIGURE 10



SAFE OPERATING CURVES
FIGURE 12

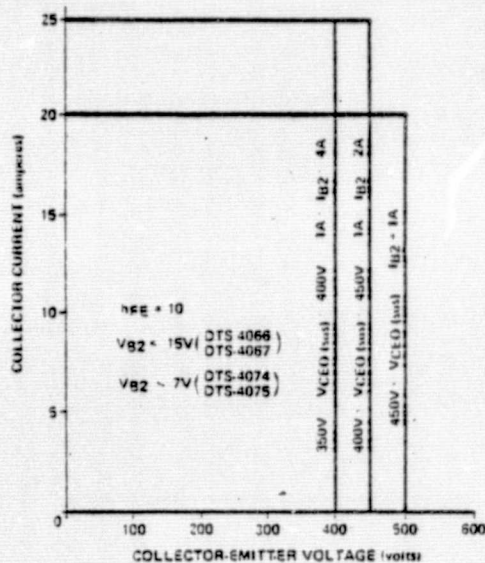
DTS-4066
DTS-4067
DTS-4074
DTS-4075

EE-22T-EMA-022

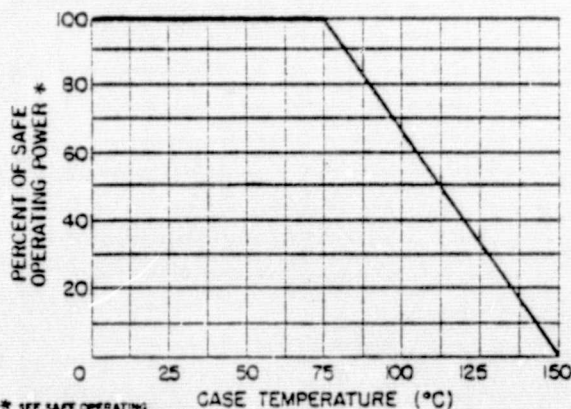
D11



Delco Electronics SEMICONDUCTORS



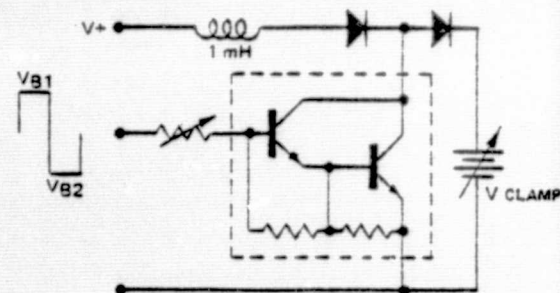
CLAMPED INDUCTIVE SWITCHING
PERFORMANCE
FIGURE 9



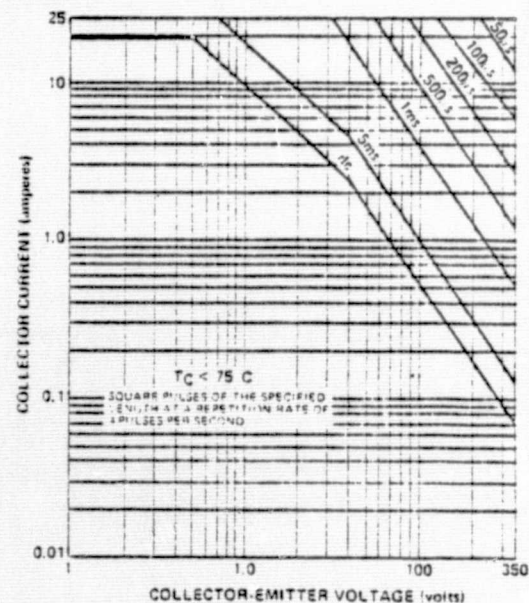
* SEE SAFE OPERATING
CURVES FOR 75 $^{\circ}C$ MAXIMUM
POWER RATINGS AS A FUNCTION OF
COLLECTOR-EMITTER VOLTAGE.

DERATING CURVE

FIGURE 11



CLAMPED INDUCTIVE SWITCHING
TEST CIRCUIT
FIGURE 10



SAFE OPERATING CURVES
FIGURE 12

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APPENDIX L

SINGLE CHANNEL
POWER ELECTRONICS BREADBOARD TESTS

This appendix contains Delco document EE-22T-EMA-023 which covers the tests which were conducted on the single-channel power electronics breadboard.

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**Delco Electronics**GENERAL MOTORS CORPORATION
SANTA BARBARA OPERATIONS
6767 HOLLISTER AVENUE
GOLETA, CALIFORNIA 93017**EE-** 22-EMA-023**ENGINEERING EXHIBIT**
(NO CHANGE CONTROL)**TITLE:** Tests of Single-Channel Power
Electronics Breadboard**BY:** A. Barrett/H. Hansen**APPROVED:** *H. Hansen***DATE:** 2-21-78INTRODUCTION

The single-channel power electronics breadboard circuits are described in EE-22-EMA-014. The power circuit utilizes the Westinghouse D60T transistors which were chosen for this application on the basis of the tests which were reported in EE-22-EMA-022. The single-channel power electronics breadboard was designed to operate at a nominal supply voltage of 270 Vdc and provide a motor current of 60 A. A number of tests were conducted on the breadboard to evaluate its operation. The results of the tests are summarized in the following paragraphs.

COMMUTATION ANGLE CONTROL

The commutation angle is selectable by means of a thumbwheel switch on the rotor position sensor (RPS) control panel. Photos 1 through 3 show the line-to-neutral open-circuit motor voltage for phase A (V_{AN}), and three of the inverter control signals (OAPON, OBPON, and OCPON), for commutation angles of 0° , 30° , and 58° . Photo 4 shows the RPS position output signal and the V_{AN} waveform.

Photos 5, 6, 7, and 8 show the effects of commutation angle on the motor phase current (I_A) and the inverter switch current (I_{AN}).

TRANSISTOR OPERATION

Photos 9, 10 and 11 show the base current waveforms of one of the power transistors. During turn-on, the base current reaches 16 A in about 600 nanoseconds. During turn-off, the reverse base current peaks at 12 A approximately 3 microseconds after turn-off is initiated.

Photos 12, 13, and 14 show both the base-emitter voltage, V_{BE} , and the base current, I_B , under typical operating conditions. At turn-on, the base is quickly driven positive, reaching 3 V in approximately 200 nanoseconds and stabilizing at approximately 1.2 V. Similarly, turn-off is achieved by rapidly reverse-biasing the base-emitter junction. V_{BE} then stabilizes at about -8 volts.

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PAGE 1 OF 11**EE-** 22-EMA-023

DRL-107 (rev 4-71)

No advance

V_{AN}

Q_{APON}

Q_{BPON}

Q_{CPON}

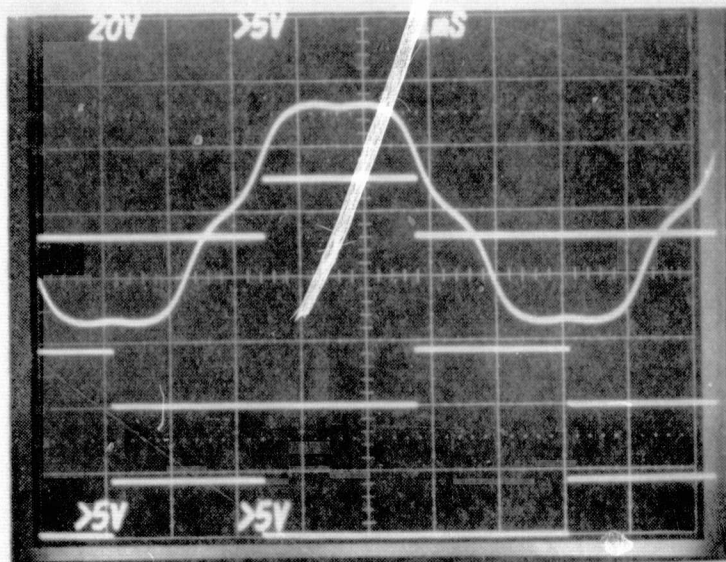
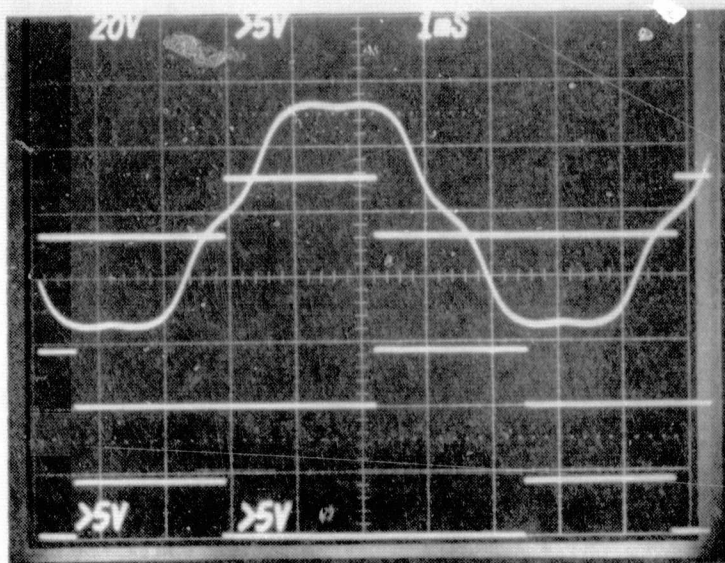


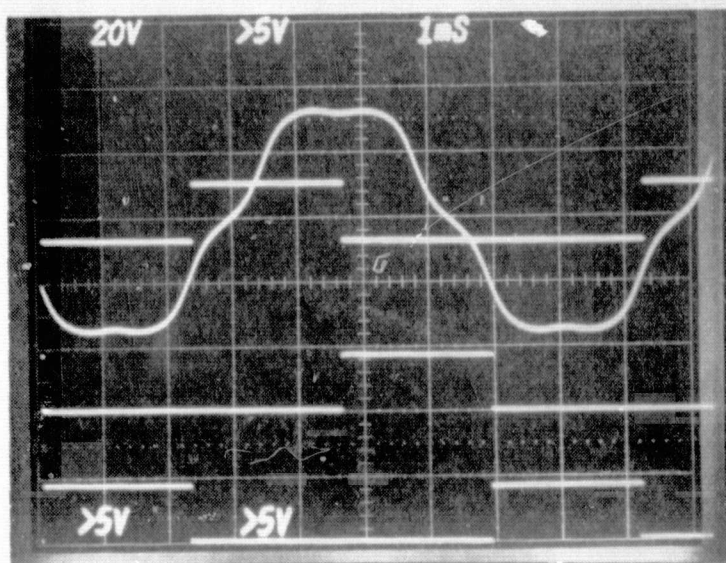
PHOTO
1

30° advance



2

58° advance

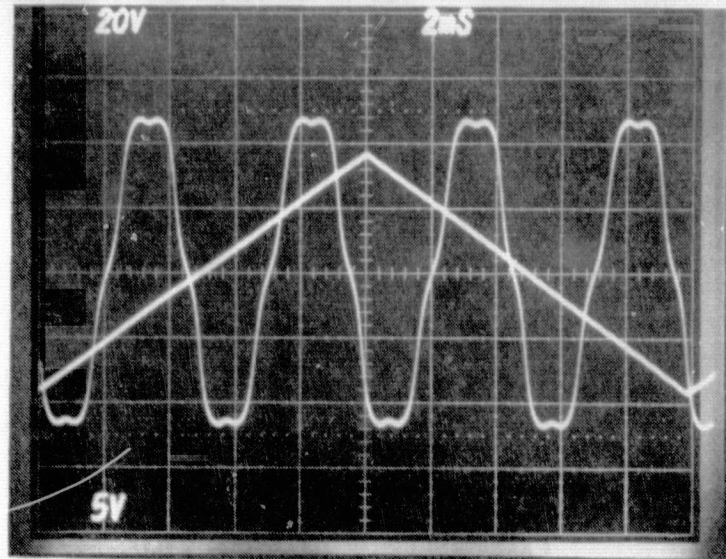


3

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V_{AN} 20V/div

RPS
position
output 5V/div



PHOTO

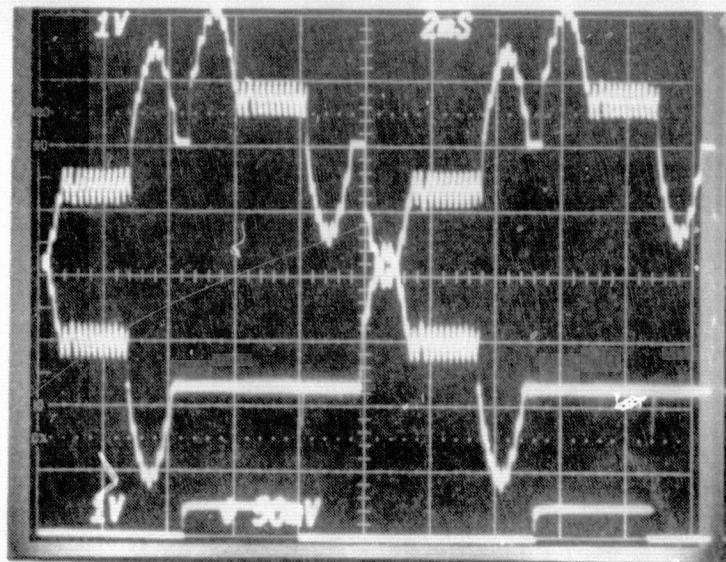
4

30° advance

I_A 10A/div

I_{AN} 10A/div

QAPON

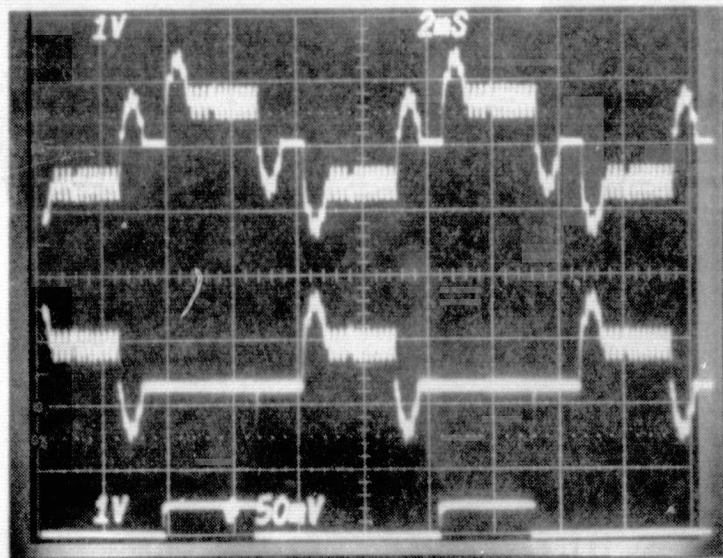


5

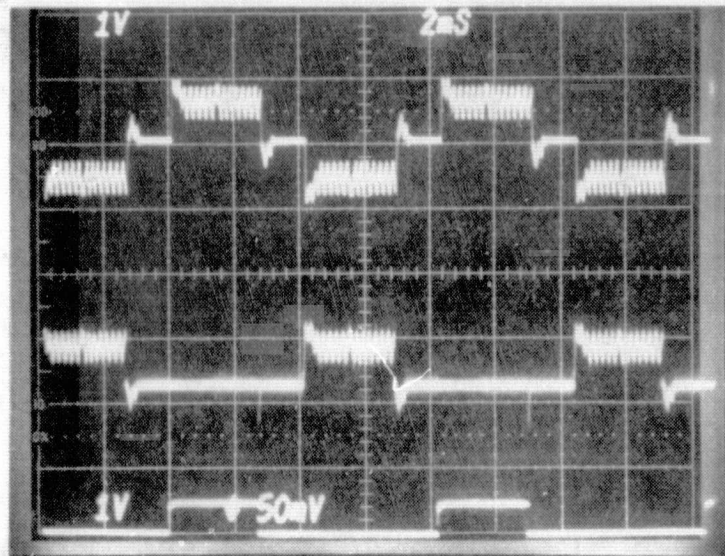
20° advance

 I_A 10 A/div I_{AN} 10 A/div

QAPON

PHOTO
6

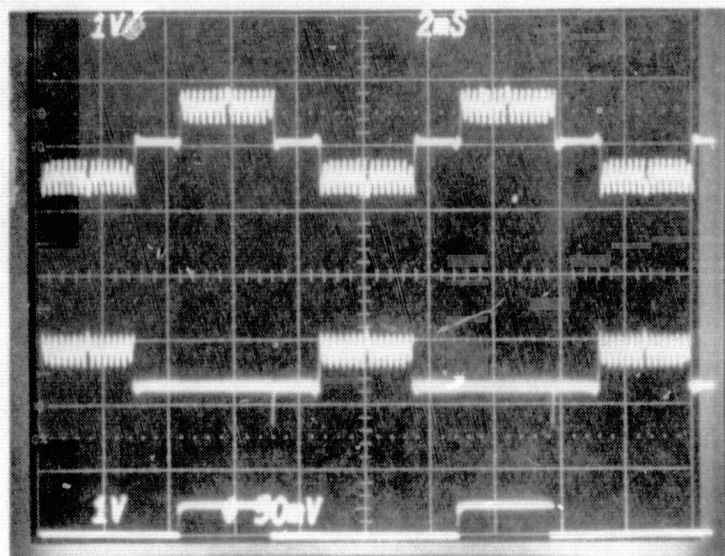
10° advance



7

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0° advance



8

Base Current
5A/div

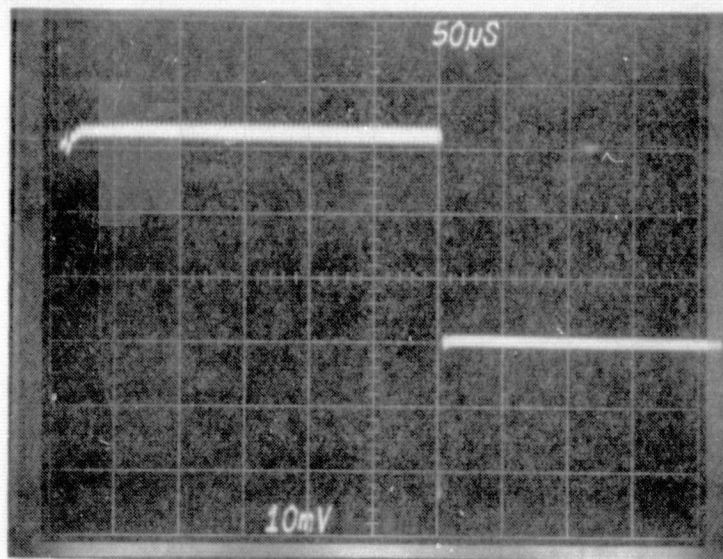
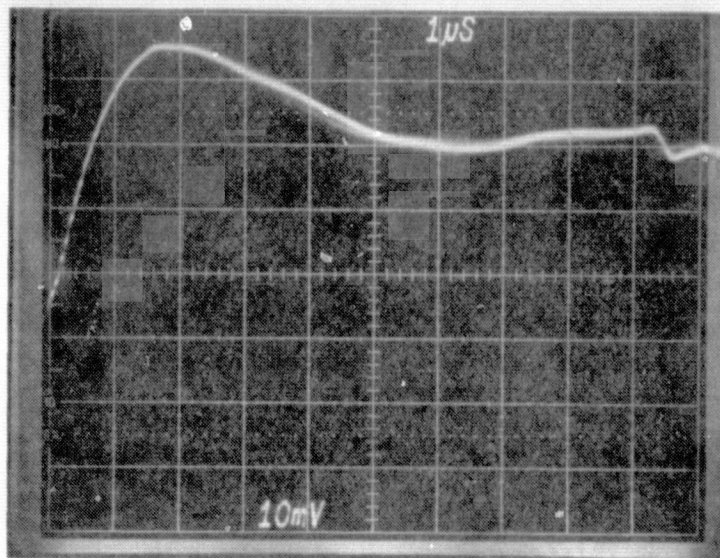


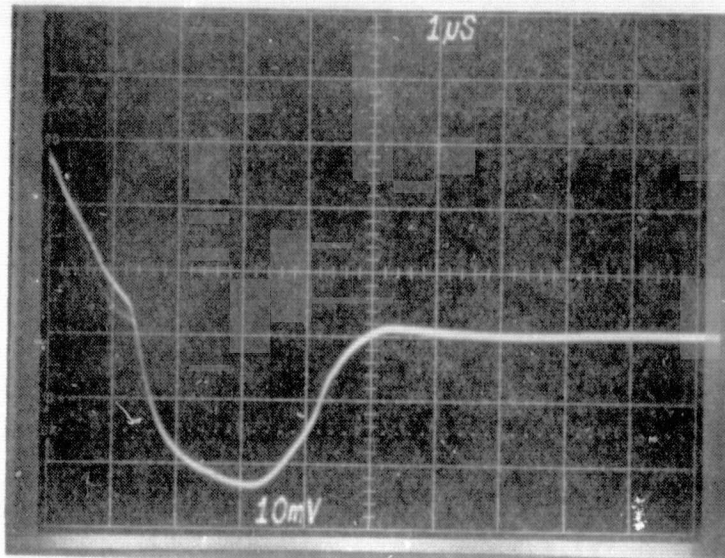
PHOTO
9

Turn-on

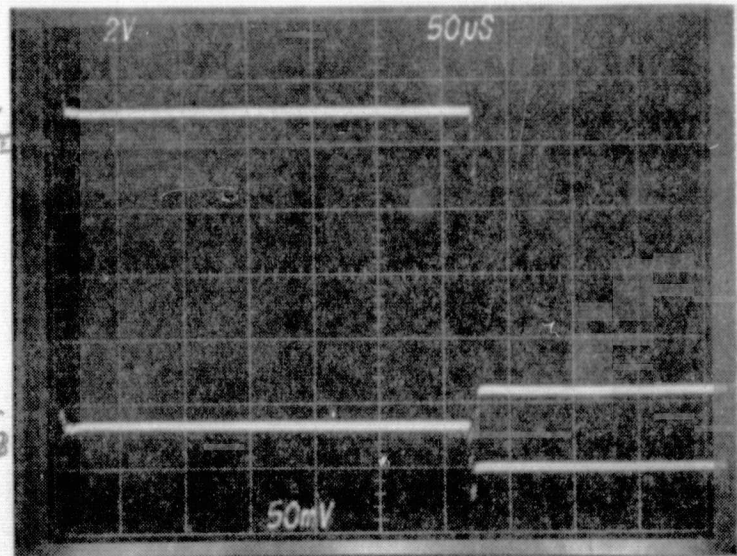
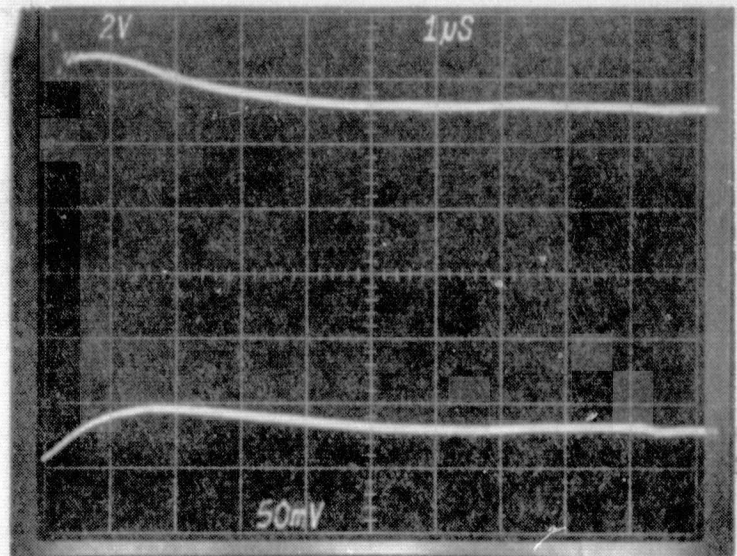


10

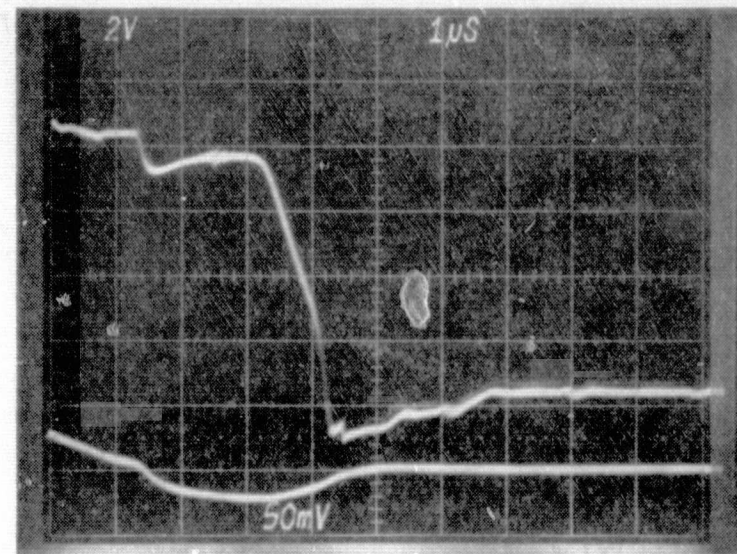
Turn-off



11

V_{BE} 2V/div I_B 25 A/div V_{BE} 2V/div I_B 25 A/div

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 V_{BE} 2V/div I_B 25 A/div

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General Motors Corporation
Santa Barbara Operations
6767 Hollister Avenue
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EE-22-EMA-023

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Photo 15 shows the collector-emitter voltage and base current for one of the motoring chopper transistors, QM1. The collector-emitter voltage drops to about 1 volt within 1.5 microseconds after turn-on is initiated, and 16 A base current is reached in about 0.6 microseconds. Photo 16 shows the collector-emitter voltage transient which occurs when the chopper transistor is turned off with a motoring current of 40 A. For this condition the snubber limits the ring-up to about 50 V. In photo 17, a similar transient for a 50 A motoring current shows the transient collector-emitter voltage exceeding the supply voltage by about 60 V. The peak voltage is reached in approximately 2 microseconds.

MOTORING WAVEFORMS

Photos 18 through 23 show a series of waveforms for nominal motor currents ranging from 10 A to 60 A. The upper trace is the current in phase C of the motor (I_C). The control signal for the motoring choppers (QMON) is shown next, followed by the current through the return diode (I_{CRD}) which couples the inverter back to the power source. The bottom trace shows the current in the current source inductor (I_L).

In Photo 18, the nominal motor current is 10 A, and the motoring chopper is on for only a small fraction of its 500 microsecond period. With a 20 A motor current (Photo 19) the chopper period is approximately 250 microseconds and the chopper is on for about 15% of the cycle. For a nominal motor current of 30 A (see Photo 20), the chopper period is about 220 microseconds, and the chopper is on about 25% of the time. Photo 21 shows the waveforms which occur at a motor current of 40 A. For this condition the chopper period is about 140 microseconds and the duty cycle is around 30%. In Photo 22 the nominal motor current is 50 A, the chopper period is about 120 microseconds and the duty cycle is about 40%.

Photo 23 shows waveforms with a nominal motor current of 60 A. It should be noted that the peak motor current for this condition is about 75 A, and the inductor current indicates that the incremental inductance of the inductor may have decreased significantly due to saturation effects. The chopper switches very rapidly during the peak current conditions, and the inductor current changes much more noticeably than the motor current. To achieve the nominal 60 A motor currents the peak currents handled by the inverter transistors are on the order of 90 A (the protection circuits were set at 95 A during this sequence of tests).

V_{CE} 10V/div

I_B 5A/div

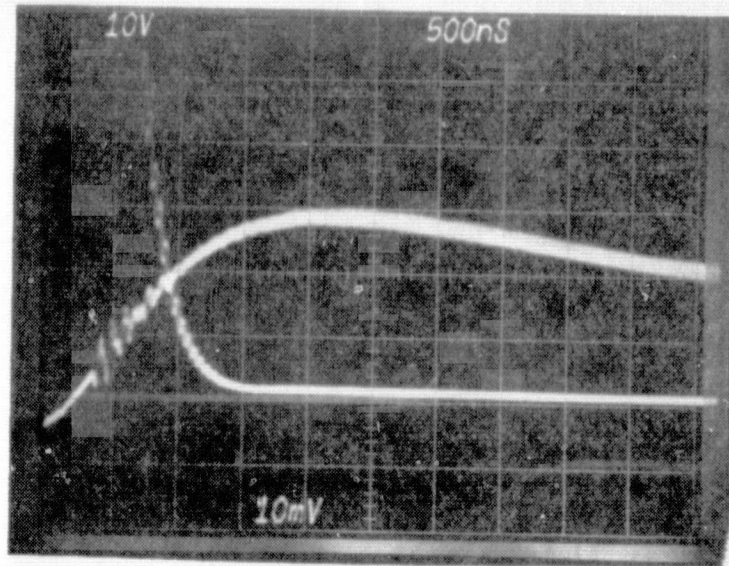
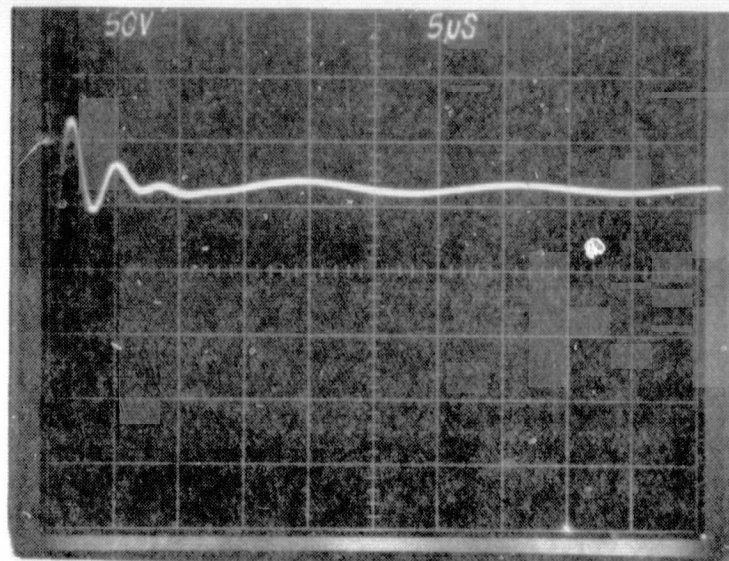


PHOTO
15

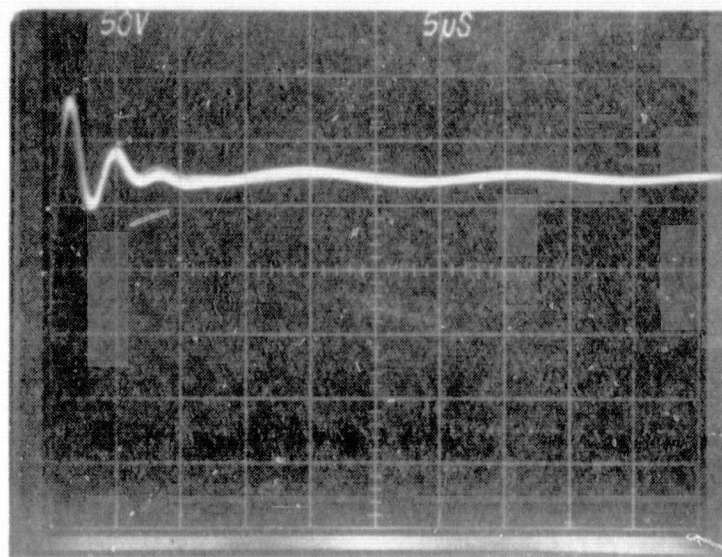
V_{CE} 50V/div
($I_m = 40A$)



16

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V_{CE} 50V/div
($I_m = 50A$)



17

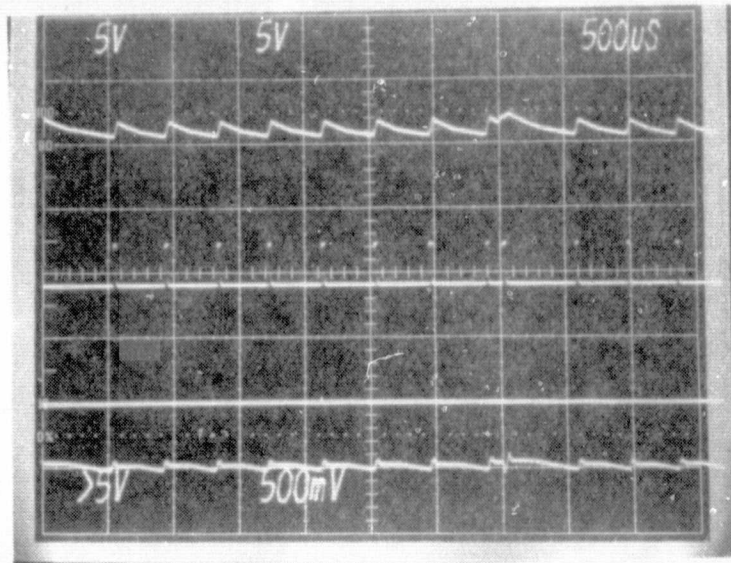
$$I_m = 10 A$$

$$I_C = 50 A/div$$

$$Q_{MON}$$

$$I_{CRD} = 50 A/div$$

$$I_L = 50 A/div$$



PHOTO

18

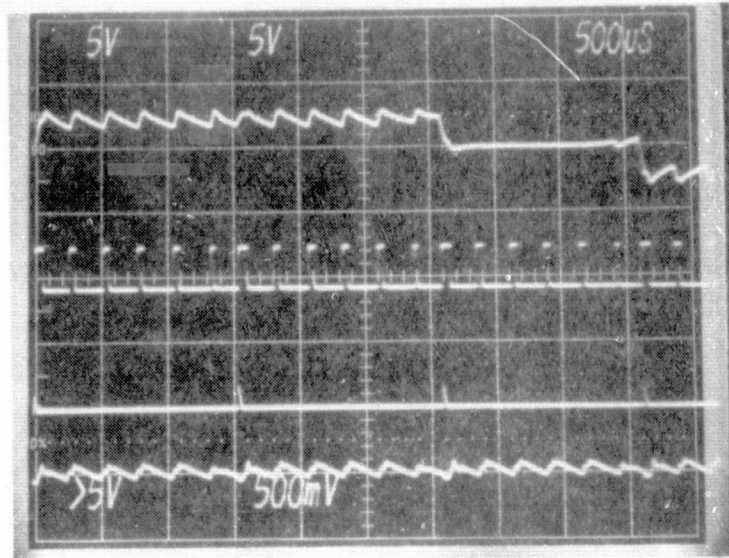
$$I_m = 20 A$$

$$I_C = 50 A/div$$

$$Q_{MON}$$

$$I_{CRD} = 50 A/div$$

$$I_L = 50 A/div$$



19

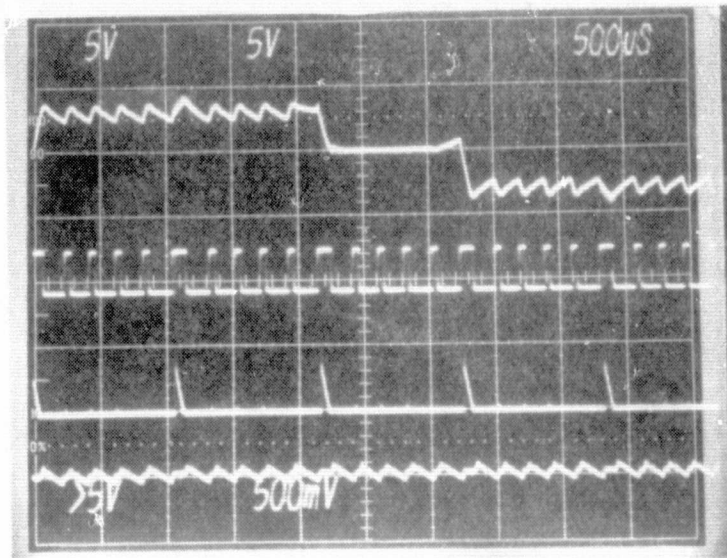
$$I_m = 30 A$$

$$I_C = 50 A/div$$

$$Q_{MON}$$

$$I_{CRD} = 50 A/div$$

$$I_L = 50 A/div$$



20

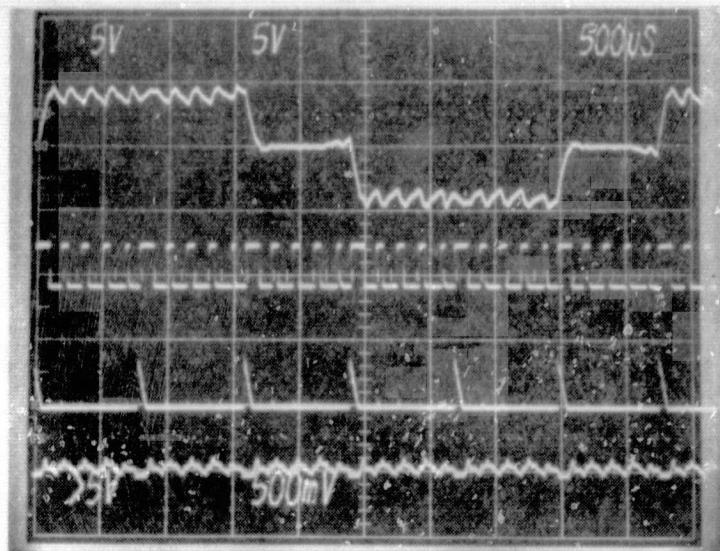
$I_m = 40 A$

I_c 50 A/div

Q_{MON}

I_{CRD} 50 A/div

I_L 50 A/div



PHOTO

21

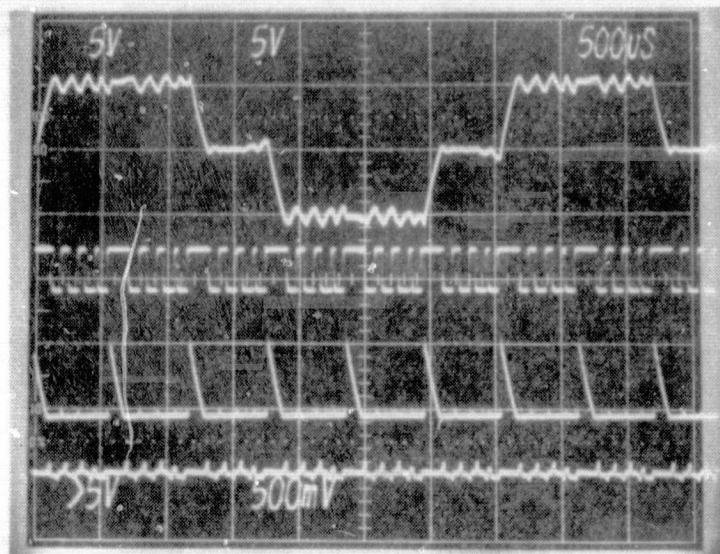
$I_m = 50 A$

I_c 50 A/div

Q_{MON}

I_{CRD} 50 A/div

I_L 50 A/div



22

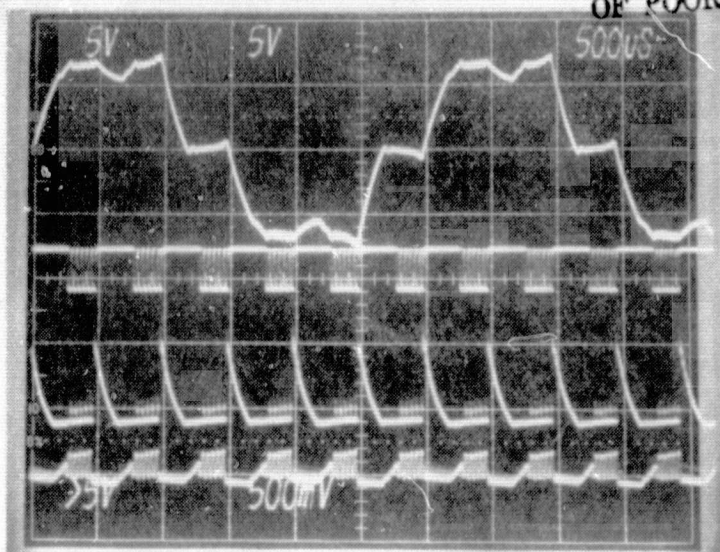
$I_m = 60 A$

$I_c = 50 A/div$

Q_{MON}

I_{CRD} 50 A/div

I_L 50 A/div



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23



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CONCLUSIONS

The single-channel power electronics breadboard has been successfully operated at full voltage and current. The snubbers which are used in the circuit limit the collector-emitter voltages to safe values, and the peak currents in the transistors are within the capabilities of the devices. The current source inductor shows evidence of saturation at the highest current levels, and should be re-designed to handle higher current levels.